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REPORT EVALUATION

Component/Criterion	Score	Multiplier	Points
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Comments:

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Abstract

The General Informative Medical Prosthetic provides sensory feedback for leg amputation patients by mapping combinational pressure differentials under the prosthetic foot and lower-leg angle measurements to distinct vibrating patterns around the remaining appendage. The system offers modes for the direct mapping of simulated sensory feedback, as well as modes to run rehabilitation training programs which affectively train the patient on how to walk correctly with a prosthetic leg. The General Informative Medical Prosthetic also offers the ability to upload bio-statistical measurements via an Ethernet interface to a standard web browser, thus giving medical professionals the ability to monitor patients remotely.

1.0 Project Overview and Block Diagram

The G.I.M.P. system serves as a patient sensory interface to existing prosthetic legs. Figure 1.1 shows the system composition as represented by a block diagram. A standard walking shoe, outfitted with an array of four pressure sensors, outputs analog voltage levels which are measured via an Analog-to-Digital (ATD) port on a Freescale MC9S12NE64CPV microcontroller. The microcontroller is interfaced to an Ethernet port which provides the G.I.M.P. system the ability to upload and tabulate bio-statistical information to a web browser terminal. An LCD is interfaced to the microcontroller and an RPG comprises the on-board user interface. Software modules provide the capability to either directly transfer pressure differentials to the vibrating motor array, or to execute "training programs" in which the patient is prompted to apply different orientations of pressure (thus aiding in the prosthetic adaptation process). The vibrating motors are connected in parallel to pull-up NPN MOSFET amplifiers (Class D) which allow for the 100mA current requirement of each motor. The power system is comprised of one 7.2V NiCd RC battery which is interfaced with a power supply outputting 5V, -5V, and 3.3V via parallel LM switching MOSFET circuits. Main battery power is monitored by one ATD pin and battery status is displayed on the LCD where "[###]" represents a full battery and "[ ]" represents an empty battery.

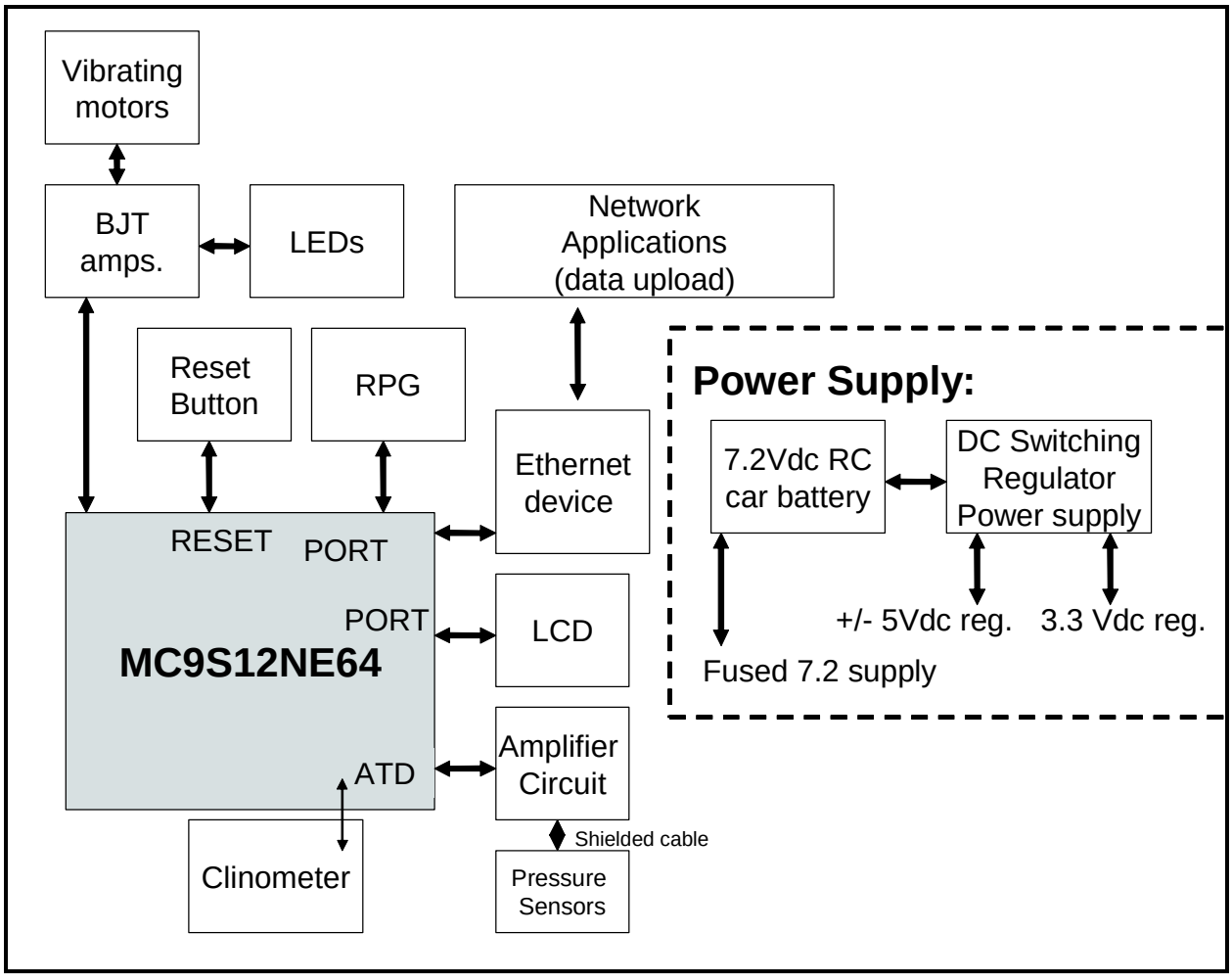


Figure 1.1 – G.I.M.P. Block Diagram

All hardware and software systems are confined to units which are easily mountable on existing prosthetic legs, as well as on the human leg (for testing purposes). Each vibrating motor is accompanied by an LED which provides visual indication of the device's operation. Figure 2.1 shows the completed G.I.M.P. system being worn by a testing subject (mounted on human leg for preliminary testing).

Figure 1.2 – Completed G.I.M.P. System

2.0 Team Success Criteria and Fulfillment

2.1 **Criterion 1:** *"The ability to detect pressure changes in the shoe via an ATD port on a microcontroller and to map those pressure differentials to distinct vibrating patterns in a vibrating motor strap."*

This success criterion is fulfilled as the device clearly maps unique patterns from the pressure sensors in the shoe to the vibrating motors strap. When each motor turns on, it's corresponding LED turns on which shows the "distinct vibrating patterns" required. The LEDs are rather dim because they are intended for operation at 5 volts and, during device operation, they are receiving a duty cycle waveform with maximum voltage of 3 volts. Figure 2.1 shows the device demonstrating Criterion 1 and Criteria 2.

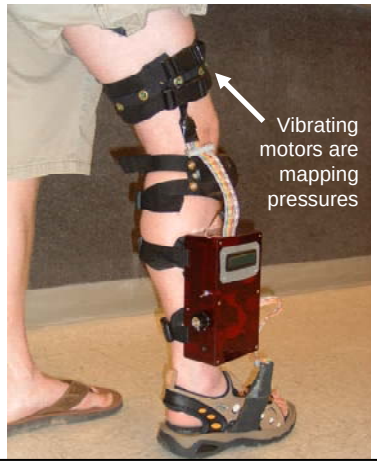


Figure 2.1 Demonstration of success criteria 1 and 2

2.2 **Criterion 2:** *"The ability to execute sequential vibrating patterns, thus providing 'how-to-walk' training capabilities".*

A sequential training program can be executed which vibrates all motors until detecting the beginning of the operator's gait phase (indicated by a reading taken from the clinometer). Once the step begins, only the motors in the back of the strap are enabled, thus indicating to the user that the heel should be placed on the ground. When it is determined that the heel is firmly on the ground, the motors on the side of the leg vibrate, followed by the motors at the front at the leg, thus indicating to the user that weight should be transferred to the front of the foot. The routine restarts when the clinometer marks the beginning of the step (when the angle of the knee with respect to the thigh is minimized).

2.3 **Criterion 3:** *"The ability to record sensor data and upload to a computer via Ethernet connectivity."*

Figure 2.2 is a screen shot of an internet browser receiving data from the G.I.M.P. device. As the type of information being transmitted during the Ethernet routine can be selected by the doctor, each is indexed and tabulated, thus allowing for easy integration into such programs as Excel and Matlab. For demonstration of this success criteria, the data being displayed is the time in the previous mode (in minutes), the device's on time (in minutes), and the number of steps taken in direct map mode.

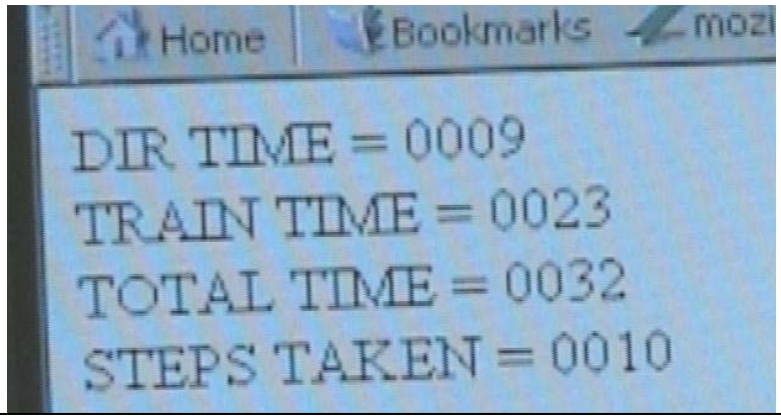


Figure 2.2 Demonstration of success criteria 3

2.4 **Criterion 4:** *"The ability to display system status (mode, battery level) on an LCD."*

Figure 2.3 is a shot of the G.I.M.P. system's LCD which displays the current mode on the top line and mode being pointed to by the RPG on the bottom line, along with the battery level (where "[###]" is a full battery and "[ ]" is an empty battery). mode is used to send data to the LCD.

Figure 2.3 Demonstration of success criteria 4

2.5 **Criterion 5:** *"The ability to automatically determine when the prosthetic is idle and enter into a power-conservation mode in which certain functions/ports will be turned off (some ATD, LCD, etc)."*

Power conservation mode is entered when the microcontroller detects inactivity in the foot sensors. During this time, the device turns off ATD and PWM pins to conserve power. To exit out of power conservation mode, the device can either be reset, or the RPG can be pressed. During the testing of this success criterion, the idle time was set to approximately 1 minute, after which time the device went into power conservation mode.

3.0 Constraint Analysis and Component Selection

3.1 Introduction

The design is a system that supplements existing prosthetic legs and provides the patient with some sensory feedback about the pressures on the foot through an array of vibrating motors worn on a strap around the thigh. The system will use four small pressure sensors placed in the insole of a shoe and a clinometer at the knee to record information about pressure on the base of the foot and which phase of stride a patient is in at the time. All of the sensors output an analog signal, which will be measured using an ATD port on the selected microcontroller. The microcontroller uses these sensor inputs to determine where there is pressure on the foot and activates the appropriate motors, which will be connected using bipolar junction transistor (BJT) amplifiers to supply sufficient current to operate the motors. The microcontroller will use memory to store statistics about how the patient has been walking and allow it to be uploaded via an Ethernet connection. The system will also use software that will allow the execution of "training programs" in which a light vibration from the motors prompts the patient to make movements and apply pressure in the proper order while they are learning to walk with the prosthetic. To distinguish between modes the microcontroller will also interface with a 16x2-character display that can display mode and other information. A rotary pulse generator will also be interfaced with the microcontroller in order to allow the patient to control the mode of the system. Finally, because the system must be portable it needs to be battery powered using a battery that will allow for a reasonable operational time between charges and will display the current battery level on the LCD.

3.2 Design Constraint Analysis

3.2.1 Computational Requirements

The microprocessor must be capable of calculating the average of the values read from the four pressure sensors in the foot to determine where pressure is being placed on the foot. It must also be able to resolve an analog signal with at least a 1V resolution and refresh the LCD display. The most important requirement is that processes be completed in real time so that the sensory feedback corresponds to the pressure that is being applied to the foot at a specific time.

3.2.2 Interface Requirements

The design requires several interface connections. Each of the four pressure sensor inputs and the clinometer input require ATD conversion. The 10 vibrating motors will be driven using BJT amplifier circuits and can be interfaced with a single I/O pin for each motor. The LCD display will require 11 pins to interface directly with the microcontroller [1]. The rotary pulse generator interface will require three pins. The Ethernet interface being used is built into both microprocessors that are under consideration.

3.2.3 Power Supply Constraints

The design requires a portable power source capable of providing a number of different supply voltages. The pressure sensors use an amplifier circuit that will require a 7.2 and -5 V supply voltages and draw no more than 2.5 mA [2]. The microprocessor will require a 3.3 V supply voltage. All CMOS parts require a 5 V supply. The clinometer requires a supply in the range of 5V to 15V with a 9V nominal value and draws only 0.5 mA of current [3]. The LCD requires 5 V and will draw 1.2 mA [1]. The largest power consumption will occur in the vibrating motors which operate at 3 V and can draw 100 mA each [4]. There is also a possible interface to off-chip memory that may be required to store the statistical data recorded.

3.2.4 Packaging Constraints

The design must be sufficiently small so that it will fit easily onto a prosthetic leg and can be worn under clothing. The vibrating motor strap must also fit easily under clothing and must be comfortable enough to be worn for extended periods. The pressure sensor array must be able to be placed easily in the insole of a typical shoe and must be able to measure pressure at the point where each sensor is located uniquely. The overall weight of the system should be light enough that the weight of the system and prosthetic combined does not exceed the weight of a typical human leg. Therefore, the device has a target weight of 2.5 lbs with an estimated maximum of 5 lbs. In addition, in order to be practical, the device must be able to withstand some exposure to the elements. Therefore, the entire system must be at least water resistant and should be able to operate within a reasonable temperature range from 50 to 95 degrees Fahrenheit as an example.

3.2.5 Cost Constraints

The cost of the design should be as low as possible to keep the final consumer cost reasonable. However, due to the nature of the system, the cost will be moderately high. The final cost will be in the area of $500 due in large part to the sensor requirements of being small and having a resolution that will allow the detection of small pressure and orientation changes.

3.3 Rationale

The pressure sensors constitute the first major component block. Because of the packaging constraints of the sensor array, the pressure sensors need to be very thin and have a relatively small area of measurement. The Transducer Techniques® Subminiature Compression Only Load Button SLB Series Load Cell was considered as an initial candidate. A thickness of 0.250 inches combined with the price of $395 per unit as specified in [5] made the package larger than ideal and far too expensive. The second pressure sensor candidate was the Flexiforce® A201 Standard Force & Load Sensor. According to the Flexiforce® datasheet [2], the device is only 0.208 mm thick and has a sensing area of 9.53 mm, which fit well into the area where the sensors will be located. In addition, the price of these sensors was only $55 for a pack of four, which made it a much better choice in order meet cost constraints.

The second major component to be selected was the clinometer. The first possible sensor was the Omron Micro Tilt Sensor D6B. This sensor measures a tilt angle using two discrete output pins as shown in datasheet [6]. This met the design's basic requirements, but a discrete output would limit that ability of the system to detect small changes in the angle of the lower leg. This led to the selection of the AccuStar® Electronic Clinometer with radiometric output as the final choice for the design. The specific clinometer selected was the AccuStar® clinometer model with radiometric output and a horizontal flange mount. According to the manufacturer datasheet [3], this sensor operates like a potentiometer with a linear analog output relative to ground and whose voltage is selected by the supply voltage. This allows a much greater resolution and fits the design requirements of tilt measurement better than the Omron sensor. The only drawback was the high price of the sensor at $139, but no other sensor could be identified which fit the requirements at a lower cost.

The final major component selection was the choice of a microcontroller. One of the most important constraints on the microprocessor is the need for Ethernet connectivity.

Based on this constraint the Rabbit Semiconductor RCM3700 RabbitCore and Freescale Semiconductor MC9S12NE64 were selected as candidates because of their integrated Ethernet capabilities. Both microprocessors would meet the computational requirements of the design, but there are differences in the amount of on chip storage and available I/O pins. The RCM3700 offers more storage with up to 512 K of flash, 31 configurable I/O lines, and 2 fixed outputs [7]. The MC9S12NE64 only has 64 K of flash, but offers up to 70 I/O lines [8]. With the number of required I/O lines near 30, the MC9S12NE64 was selected because it allows more available lines for debugging and expansion. The additional I/O lines also allow for the possibility of interfacing with off-chip memory to compensate for the smaller on-chip flash.

3.4 Major Components

Description	Vendor	Part Number	Unit Cost	Quantity	Total Cost
FLEXIFORCE SENSORS	Tekscan	A201-100	$13.75	4	$55.00
SENSOR CLINOMETER HORIZONTL FLNG	AccuStar	02110102-000	$139.00	1	$139.00
VIBRATING MOTORS	Sanko Electric	1E120	$1.25	10	$12.50
MC9S12NE64V1	freescale semiconductor	MC9S12NE64CPV	$0.00	1	$0.00

4.0 Patent Liability Analysis

4.1 Introduction:

As the primary focus of the G.I.M.P. device is adaptability to fit a large variety of prosthetic legs, it is not intended to compete with existent prosthetics themselves, but rather is meant to be an optional tool used by patients who wish to expedite their recovery time in a more autonomous manner than is currently available. The prosthetic itself is not modified at all in the operation of the device and in fact, the device can be demonstrated on any individual as it can fit onto a human leg as well as a prosthetic. Therefore it is necessary not only to examine prosthetic patents, but also patents involving all of the peripheral devices used by the G.I.M.P. system including shoes equipped with pressure sensors, vibrating motor feedback devices, and the use of clinometers to measure the angle of the lower foot.

4.2 Results of patent search:

There are numerous existing devices that serve the same function as the in-shoe pressure sensor array and the vibrating motor strap. One device was found in which pressure sensors in the foot of a prosthetic are interfaced to vibrating motors around the existing limb, thus serving essentially the same function as the G.I.M.P. system. The following sections will elucidate each similar device found on the United States Patent and Trademark Office search engine [1].

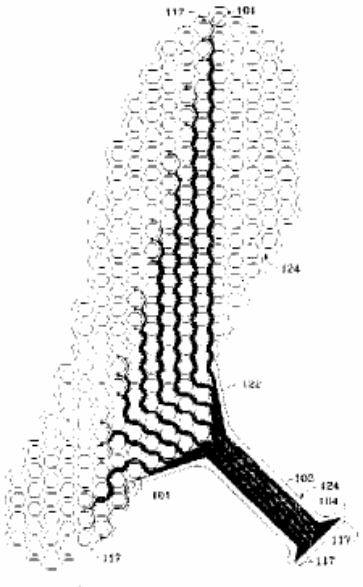


Figure 4.1: System for continuously measuring forces applied by the foot (US patent # 5,678,448

4.3 Existing Devices Similar to G.I.M.P. Peripherals:

There exists a sensor array (pictured in figure 4.1) which is intended to perform essentially the same task of measuring pressure changes of the foot on the ground. In the G.I.M.P. system, these pressure changes are interpreted by the microcontroller before being mapped to vibrating motor patterns. Two patents exist for this foot-shaped pressure sensor array for detecting pressures applied by the foot and pressures applied on the foot [2] [3], each corresponding to a different configuration of the device.

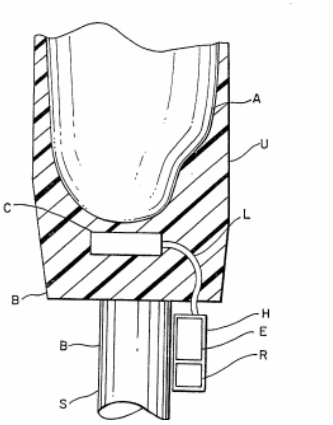


Figure 4.2: Sensor device for monitoring a prosthetic device (US Patent #5,840,047)

While the G.I.M.P. system measures the position of the prosthetic relative to the ground using a clinometer, another device accomplishes essentially the same function by measuring the prosthetic's position relative to the patient's leg. As described by its patent, "The ***sensor*** and alarm system for monitoring a relative position of a prosthetic device with respect to the residual portion of an amputee's limb includes a battery power supply; a proximity ***sensor*** for generating a position signal indicative of the relative position of the prosthetic device and the residual portion in the prosthetic device near the residual portion, and an alarm device for signaling when the prosthetic device is located in an injurious position or positions."[4] A picture of the sensor for monitoring a prosthetic device is shown in Figure 4.2. Note that the sensor itself is notably different than the clinometer used on the G.I.M.P. system, but the functionality it provides is practically identical (determining the position of the prosthetic).

4.4 Existing Devices Similar to Overall G.I.M.P. System:

Only one US Patent was found which essentially captivates the overall functionality of the G.I.M.P. system. The system and method for providing a sense of feel in a prosthetic or sensory impaired limb [6] is an apparatus for providing a person with stimuli corresponding to an external operation on a sensor of a prosthetic device used in conjunction with a prosthetic or sensory impaired limb. The specific limb mentioned in the US patent is the leg and, therefore, this system provides the same functionality of one of the success criteria of the G.I.M.P. system; mainly, "The ability to detect pressure changes in the shoe via an ATD port on a microcontroller and to map those pressure differentials to distinct vibrating patterns in a vibrating motor strap." A picture of this patented device can be seen in Figure 4.4. Note that the device has both pressure detection sensors as well as vibrating motors located around the existing appendage, although the system is a complete prosthetic itself rather than a system that can be added to an existing prosthetic (like the G.I.M.P. system).

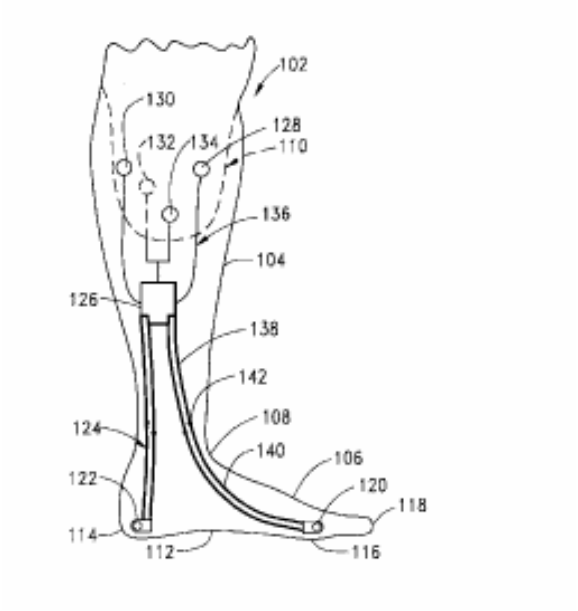


Figure 4.3: System and method for providing a sense of feel in a prosthetic or sensory impaired limb (US Patent #:6,500,210)

4.5 Analysis of patent liability:

In the following section, each of the "similar" devices found in the patent search will be analyzed under the terms of literal infringement and infringement under the doctrine of equivalents as the two types of infringement have been defined in the following ways: If the potentially infringing product or process literally has all of the limitations recited in a claim, it is said to "literally infringe." However, even if one or more elements or limitations are not literally present, the potentially infringing product or process might still be found to infringe under an equitable doctrine developed by the courts, called the "Doctrine of Equivalents." While no patents were found that infringe with the overall G.I.M.P. system in *all* aspects, there are several

areas of possible infringement centric around the system's peripheral devices and *individual* success criteria. The patents listed below were filed in 2001.

4.6 Analysis of Patent #5,323,650 and #5,678,448 with Respect to the G.I.M.P System:

The pressure sensor for the foot and the corresponding configuration patent (sensor lies between the foot and the shoe) would infringe with the foot sensors of the G.I.M.P. system under the definition of literal infringement since each system provides identically the same features. This infringement, however, would not be a legal issue since the G.I.M.P. system is built from and is therefore inclusive of this particular patent. The pressure sensors used between the foot and the shoe of the G.I.M.P. system were purchased from the company which owns rights to patent #5,323,650 and #5,678,448. In other words, because we are not attempting to manufacture the same device but rather to integrate it into a larger system, no patent infringement would occur as long as the foot pressure sensors were purchased from the FlexiForce ® Corporation prior to installation.

4.7 Analysis of Patent #5,840,047 with Respect to the G.I.M.P System:

As was noted in the description of its patent, this method for measuring the position of the prosthetic leg uses a reference to the remaining appendage rather than in reference to ground. Under the definition of each type of patent liability, the G.I.M.P. system and this patent "perform [essentially] the same task" but, because they do so in different ways and using different technologies, there would be no patent infringement. It should be noted that the type of sensor used by this patent may actually minimize the volume occupied by the G.I.M.P. system should it be utilized, but the cost of the associated royalties would have to be considered before it would be integrated into the system. As it is, no infringement occurs, but the G.I.M.P. device is potentially not as efficient as it could be.

4.8 Analysis of Patent #5,775,332 with Respect to the G.I.M.P System:

While this patented device is not intended to be used by patients with leg amputations, it provides much the same functionality as is described by the operation of the G.I.M.P. system. Mainly, each device "provides bio-sensory feedback to the patient" in a way that is meant to aid

with rehabilitation. This device teaches patients who have suffered strokes how to walk again by using sequential feedback patterns like those that are performed in the motor strap of the G.I.M.P. system. Although the two systems provide much the same function in much the same way, the literal specificity of the G.I.M.P. system sets it apart from this patent. As long as the device is marketed as being intended specifically for prosthetic patients and not for stroke victims, there should not be any infringement. This could be an issue as far as immediate demonstration goes as the inventors of the G.I.M.P. system are planning on demonstrating it on a human leg. Should the device be demonstrated for actual consideration, it is recommended that a model be used with an actual prosthetic limb.

4.9 Analysis of Patent #6,500,210 with Respect to the G.I.M.P System:

This patent proposes the largest possibility of patent infringement to the G.I.M.P. system. While this patented device is intended to communicate pressure differentials in the foot to vibrations around the existing appendage, it does so through an already-integrated prosthetic limb whereas the G.I.M.P. system is intended as a "addable system" to existing prosthetics. This means that, while it provides the same function, it does so in a substantially different way. Furthermore, the G.I.M.P. system is capable of many other modes (like training mode) as it incorporates a microcontroller which has the capacity to execute programs. This function is not described by Patent #6,500,210. For these reasons, it has been determined that the G.I.M.P. device does not infringe on this patent under the definition of "literal infringement", although it may infringe under the doctrine of equivalents since one of its modes provides direct sensory feedback (no stored sequential program is executed in this mode).

4.10 Action Recommended:

As it has been determined that there is possible patent infringement under the doctrine of equivalents with patent #6,500,210, some device modifications and marketing strategies will now be suggested to prevent such infringement. Firstly, when the G.I.M.P. device is being considered for a patent, it should be emphasized that the device provides a unique function by acting as an "addable system to existing prosthetics" and thereby does not infringe with patent #6,500,210 as it provides its function in a substantially different way. The difference could be compared to a car-mounted CD player versus a portable CD player (each of which holds its own

unique patent currently). Secondly, in order to ensure that the G.I.M.P. system does not infringe, it is recommended that that "direct sensory" mode be eliminated from the device. This means that the G.I.M.P. system would only execute training programs rather that directly communicate pressures on the bottom of the foot to vibrations around the leg. While substantial functionality would be lost, it is clear that the device would still be of clear value to the recovering amputee and would, without a doubt, be patentable under US law.

5.0 Reliability and Safety Analysis

5.1 Introduction

Since our device will most likely be used by patients who would have trouble walking with an ordinary prosthetic, there is a chance one could become dependant on the sensations to walk, and a failing prosthetic could confuse them, causing them to trip and fall. While we feel that extensive field testing would need to be done to show this dependence to be the case, we have chosen to be cautious and will still consider multiple motor failures to have a high criticality. Since each discrete "instruction" to the user makes use of multiple motors, however, we will deem a single malfunctioning motor an "inconvenience" and therefore label it a "semi-critical" failure. The acceptable failure rate for this "semi-critical" failure will be explained in the reliability analysis section of this document, and is higher than the standard 10^{-9} failure rate for failures resulting in possible safety hazards.

5.2 Reliability Analysis

1. Microcontroller MC9S12NE64CPV

   $\lambda_P = [C_1 * \Pi_T + C_2 * \Pi_E] * \Pi_Q * \Pi_L$ [1]

   where:

   C_1 – die complexity (16 – bit [4]) = 0.28

   Π_T – temperature coefficient ($T < 125^oC$ [4]) = 3.1

   C_2 – Pin constant (112 pins [4]) = 0.046

   (Interpolated between 80 and 128 pin table entries of 0.032 and 0.053 [1])

   Π_E – Environmental Constant (Ground Mobile) = 4.0

   Π_Q – Quality Factor (Commercial) = 1.0

   (Commercial is normally 10, but Dr. Johnson indicated in lecture that a value of 1 should instead be used for Π_Q)

   Π_L – Life Constant (In production for about six months [4]) = 1.8

   Thus:

   $\lambda_P = [0.28 * 3.1 + 0.046 * 4.0] * 1.0 * 1.8$

   $\lambda_P = 1.894$ failures per 10^6

   $MTTF = 1/\lambda_P$

   MTTF = 5.28E5

2. Step Down and Inverting DC/DC Converter LTC1174HV-5

$\lambda_P = [C_1 * \Pi_T + C_2 * \Pi_E] * \Pi_Q * \Pi_L$ [1]

where:

C_1 – die complexity (assumed 301 to 1000 transistors) = 0.04

Π_T – temperature coefficient (T < 125°C for linear MOS device [5]) = 58

C_2 – Pin constant (8 pins [5]) = 0.026

Π_E – Environmental Constant (Ground Mobile) = 4.0

Π_Q – Quality Factor (Assumed Class B) = 1.0

Π_L – Life Constant (In production for over two years [5]) = 1.0

Thus:

$\lambda_P = [0.04 * 58 + 0.026 * 4.0] * 1.0 * 1.0$

$\lambda_P = 2.424$ failures per 10^6

$MTTF = 1/\lambda_P$

MTTF = 4.13E5

3. Transformer CTX100-4

$\lambda_P = \lambda_B * \Pi_Q * \Pi_E$ [2]

where:

λ_B – Base failure rate (T_{HS} = 125°C, Max Operating Temp = 130°C [6]) = 0.016

Π_Q – Quality Factor (assumed less than MIL-spec) = 30

Π_E – Environmental Constant (Ground Mobile) = 12

Thus:

$\lambda_P = 0.016 * 30 * 12$

$\lambda_P = 5.76$ failures per 10^6

$MTTF = 1/\lambda_P$

MTTF = 1.74E5

4. Switching Transistor BJT 2N3704.

$\lambda_P = \lambda_B * \Pi_T * \Pi_A * \Pi_R * \Pi_S * \Pi_Q * \Pi_E$ [3]

where:

λ_B – Base failure rate (NPN [7]) = 0.00074

Π_T – temperature coefficient (T < 100°C [7]) = 4.2

Π_A – Application Factor (switching) = 0.70

Π_R – Power Factor (P_r < 1W) = 1.0

Π_S – Stress Factor ($0 < V_S < 0.3$) = 0.11

Π_Q – Quality Factor (Plastic DIP) = 8.

Π_E – Environmental Constant (Ground Mobile) = 9.0

Thus:

$\lambda_P = 0.00074 * 4.2 * 0.70 * 1 * 0.11 * 8 * 9$

λ_P = 0.0172 failures per 10^6

MTTF = $1/\lambda_P$

MTTF = 5.804E7

5.3 Conclusions

The microcontroller, switching and inverting DC regulator and the transformer all had failure rates in the 10^{-6} range, which may be acceptable as these would lead only to system failures of low criticality. In addition, these calculations used fairly conservative estimates, especially when dealing with maximum temperate ranges. The failure rates could be further minimized by adding heat sinks and will also decrease due to the power conservation techniques we will be implementing with our design.

The switching transistor could potentially lead to a safety risk, however, as described in the introduction. 10^{-9} is generally considered an acceptable failure rate for failures that can lead to personal injury for the user. In this case the failure rate for the switching transistor is in the 10^{-8} range, somewhat higher than the 10^{-9} normally used as the guideline. The vibrating motor strap has ten different motors on it, however, each with its own switching transistor. Given that the discrete sensations being sent to the user will be using multiple vibrating motors at a time, the malfunctioning of only one BJT will fall far short of rendering the device useless and will certainly not result in a risk of personal injury for the user. The malfunctioning of two motors is still unlikely to pose a safety risk, but if we are conservative and do in fact say that two malfunctioning motors will cause a safety hazard, the failure rate of two independent BJTs is then $(1.72 * 10^{-8})^2 = 2.95 * 10^{-16}$, which certainly falls within the 10^{-9} acceptable range for a critical failure.

6.0 Ethical and Environmental Impact Analysis

6.1 Introduction

This document details the ethical and environmental impact of the General Informative Medical Prosthetic (G.I.M.P.) device being developed by group nine. The device is intended for use with existing lower limb prosthetics as an accessory or as integrated technology that aims to resolve bringing the sensation of walking back to lower limb amputees through the use of electronic sensors and motors. The device is intended to be used for normal daily use if it is integrated into current prosthetic designs. If not, it can be used as a training tool by doctors in order to aid new amputees in learning how to walk with lower limb prosthetics. This report outlines the ethical challenges that must be resolved in bringing the design to market including sufficient testing of the medical device to abide by both in-house and federal regulations, placing clear and concise warning labels and providing extensive user documentation to make incorrect use of the product clear to the user, and adding safety mechanisms for critical failures of the device. This report also outlines the environmental impact the design will have at various stages of its life cycle including techniques used in the production of the device, proper maintenance by the user during its useful life, and proper disposal and recycling of the various components used to construct the device.

6.2 Ethical Impact Analysis

Due to the nature of the G.I.M.P. device as a medical product, it is of vital importance that the product is safe for use and that any and all critical failures possible are found during testing cycles and addressed through warning labels, documentation, and safety mechanisms to ensure proper functionality in order to aid individuals who require or desire use of the product.

In order to bring the product to market, extensive testing in a variety of conditions will be necessary in order to meet in-house guidelines and reliability specifications as well as federal guidelines and regulations. For example, the device will be classified as a “medical device” in accordance with the U.S. Food and Drug Administration by its following definition: “an instrument, apparatus, implement, machine, contrivance, implant, in vitro reagent, or other similar or related article, including a component part, or accessory which is: intended for use in the diagnosis of disease or other conditions, or in the cure, mitigation, treatment, or prevention of

disease, in man or other animals, or intended to affect the structure or any function of the body of man or other animals, and which does not achieve any of it's primary intended purposes through chemical action within or on the body of man or other animals and which is not dependent upon being metabolized for the achievement of any of its primary intended purposes" [1]. Due to this classification, the device will be subject to both premarketing and postmarketing regulatory controls and approvals through extensive testing and validation studies. These regulations include the placement of proper warning labels to inform the user of immediate dangers with improper use of the device. For example, in order to prevent potential electrocution, warning labels must be provided that explicitly communicate to users environments and uses for which the product was not designed including environments where it will be exposed to water, such as in the rain, shower, etc. and so must be powered down unless the device is integrated with water-proof prosthetics. Lastly, before the product can be brought to market, it is also necessary that safety mechanisms be added to the design as critical failures are found during the testing and evaluation cycles in order to ensure user safety when/if the device enters unexpected states.

In order to address the ethical challenge of properly testing the device before bringing it to market extensive test cases and test plans will have to be developed over multiple test cycles in order to find as many faults with the device as possible before the product is sent for review by the FDA. A significant portion of these testing cycles will include operation of the device in various environments in addition to its intended use in a doctor's office or in the patient's home. For example, it is quite likely that the device will not provide enough simulation of walking with a real leg to assure a user that he/she will be able to hike a trail or scale a mountain. Although these may be extreme examples, it is important that the documentation provided with the device make the user aware of the limitations of the device in returning "full-functionality" back to their lower limb. In addition, testing will also help in determining the specifications of the device, such as the useful life of the device and how much time a user has to replace the battery in the device once the device enters a "battery-low" mode.

Providing warning labels is a challenge due to the limited space available directly on the device. There are several important warnings that must be made clear to the user, such as: the device uses a battery and so should not be placed or left in hazardous areas (in direct sunlight), the device should not be exposed to water while in use, and that the battery should be replaced or recharged as soon as possible after the device enters a "battery-low" mode should the use of the

device be critical. Placing every warning label possible on the device, however, is not acceptable since then it is entirely possible that the labels will simply be ignored. Usability studies may lead to findings that describe which warning labels are most effective and/or needed for the device and so testing will hopefully lead to the development of effective product warning labels. In addition to the warning labels, extensive documentation will have to be written for the product before it can be released to market outlining additional warnings and precautions that must be taken into consideration when using the device.

Although the "battery-low" mode is a safety mechanism developed at the time the device was prototyped, additional testing will very likely expose critical failures that can be addressed through safety mechanisms. For example, one critical failure that is quite possible is the output motor strap of the device vibrating erratically during either the direct-mapping or learning modes. In either situation, the output to the user may be confusing, disorienting, and if the user is in a dangerous environment, incorrect operation of the device could potentially cause him/her harm. A safety mechanism that could be put in place to prevent such a situation from happening could perhaps be an emergency stop button to immediately cut power to the output vibrating motors, or a software routine to monitor the output to the motors and ensure proper behavior by perhaps resetting the device if erratic output is detected.

Extensive testing and reviews are necessary for all three components of the ethical challenges faced in bringing the product to market. Through extensive testing, additional critical failures, safety mechanisms, user behavior can be studied to improve the device and create a reliable, safe, and effective product.

6.3 Environmental Impact Analysis

As with the large majority of electronic devices, there is a significant concern with the environmental impact of the G.I.M.P. device due to the hazardous materials contained in the electronic components used in its construction. These hazardous materials have the potential to harm the environment and even humans through contamination of water-supplies and potentially even food-sources [7, 8].

During production of the device, lead is used in both the traces placed on the printed circuit board in addition to the solder used to populate the board. Lead is a heavy metal that can harm both the environment, through contamination, and humans through ingestion from water,

foods, etc. This manufacturing process undoubtedly will produce waste lead that will have to be disposed of properly so as not to contaminate the nearby environment possibly even putting human lives at risk. In addition, the device will be produced with a Nickel-Cadmium (Ni-Cd) dry-cell rechargeable battery that the user will have to be aware of so the device is not placed in hazardous environments (in direct sunlight, in extreme temperatures, in water, etc.) during normal use. Doing so could cause the battery to leak and/or explode potentially causing harm to the user and/or the environment. Proper disposal and recycling is of significant importance with the device due to the use of the Ni-Cd battery and the lead found in the printed circuit board. Improper disposal of the battery or the printed circuit board can lead to contamination of the land and/or the air due to the heavy metals contained in both components.

In order to reduce the risk of contamination to the environment during production of the device, it is possible to seek alternative printed circuit board production methods through the use of lead-free printed circuit board fabrication. According to Bob McGrath of *Printed Circuit Design & Manufacturing*, "Upcoming methods to attain lead-free fabrication include using electrolytic nickel/gold for PCB surface finishes and tin, silver, and copper (SnAgCu, SAC) alloys for soldering instead of tin/lead alloys" [2]. Part of the drive for lead-free electronics production is due to the upcoming European Commission directives 2002/95/EC and 2002/96/EC, or the Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) and the Waste Electrical and Electronic Equipment (WEEE) directives respectively, that will go into full effect July 1, 2006 [3, 4]. These directives affect all parties involved in manufacturing, selling, distributing, recycling, or treating electrical and electronic equipment in Europe and so will affect policies in effect worldwide. World-leading test and certification labs such as the Underwriters Laboratories Inc. have already initiated compliance programs to adhere to the new directives [5]. One potential source where the G.I.M.P. printed circuit board could be manufactured "lead-free" includes the PCBexpress fabrication company [6].

Warnings, recommendations, and unambiguous documentation will have to be provided to inform the user of the dangers to the environment should the device and battery be mishandled or not maintained properly. These labels and documentation will have to explicitly state which environments the device should not be used in or left in. It may potentially be effective to include plausible damages to the environment should the device not be disposed of or recycled properly with an emphasis of how such damage could affect the user.

Lastly, in order to address the environmental concerns with the disposal and recycling of the product, both extensive documentation and potential recycling plans could be put in effect to curb potential harm to the environment. For instance, documentation can provide lists of authorized recycling companies and locations for both the Ni-Cd battery as well as the printed circuit board. If partnerships with authorized recycling corporations like the Rechargeable Battery Recycling Corporation (RBRC) could be made in order to streamline the process of returning the Ni-Cd batteries, users could be given both instructions on how and where to return their batteries and incentives such as rebates for returning their batteries in order to encourage proper recycling of the batteries instead of improper disposal The RBRC is a non-profit, public service organization created to promote the recycling of portable rechargeable batteries [7]. A similar service could be provided to reduce the negative environmental impact caused by the lead in the printed circuit board should lead-free production not be feasible. With respect to products integrated into prosthetic devices, collaborations could be made with retailers to initiate a "reuse & recycle" program in which used prosthetics returned to retailers could be purchased by or donated to the manufacturer where the prosthetic shell could be reused, the lead in printed circuit boards could be recycled, and the batteries could be removed and shipped to authorized recycling services like the RBRC.

7.0 Packaging Design Considerations

(All G.I.M.P. packaging pictures can be found in Appendix B)

7.1 Introduction

The system was developed to interface to or fit on current lower limb prosthetics and so size and weight were critical design constraints that the team faced since a device that is either too bulky or too heavy will not fit a lower limb prosthetic and/or would eliminate any significant positive experience perceived by a lower limb amputee. Furthermore, with a small design, the end product or technology could feasibly be marketed to existing prosthetic device manufacturers as a system that could easily be added to their products either as a marketable accessory, or as a technology that could be integrated with their devices. For testing and prototyping purposes, the device was built as an accessory for existing prosthetic devices. This added characteristic required that the packaging of the design be modular and easily fitted to existing prosthetics.

7.2 Packaging Specifications and Design

The group first learned of commercial products similar to the design when team member Nathan Smith read an article about a bionic prosthetic device in the February issue of WIRED magazine. After informing the group, significant research was done in order to determine if commercial products exist that fulfill the project's desired functionality. Although the group did not find any products that directly address returning the sensation of walking to lower limb amputees, several similar products including the C-Leg® by Otto Bock® [1] and the Rheo Knee™ by Össur [2] were found. Both commercial products are similar to the design; however, they focus on using electronics and sensor systems to correct the function of the prosthetic device and ease the process of walking for the amputee, whereas the group's product focuses on returning the sensation of walking to the lower limb amputee. This key difference leads to unique constraints for both the commercial products as well as the group's product, including significant packaging design differences. The following provides an in-depth analysis of the two

similar commercial products found by the group mentioned above: the C-Leg® and the Rheo Knee™.

I. C-Leg® by Otto Bock® [1]

Figure 1. C-Leg® by Otto Bock®

The C-Leg® is marketed as a smart prosthetic device that able to think for you using inbuilt sensors and a micro-controller to adjust itself, providing both stability and security to lower limb amputees. The packaging of the device includes a knee angle sensor at the top of the frame of the device that measures the flexion angle and the angle speed of the knee joint and a moment sensor that measures the moments of flexion by strain gauges in the ankle area. Both of these sensors along with the microcontroller and a rechargeable battery are found within a carbon fiber frame that provides high stability and yet is very light. As one can see in Figure 1., the frame of the device is quite compact allowing the user to easily conceal the device under a pant leg or skirt.

7.2.1 Positive aspects of the commercial product's packaging

The most attractive feature of the C-Leg® beyond its technological capabilities is most definitely its attractive, discrete design. The packaging of the design allows the user to either show off their prosthetic with its stylish frame or hide the prosthetic simply by covering the device with their lower garment (a pant leg, long skirt, etc). Furthermore, according to the

device's documentation [1], the user can easily switch between special activity settings including a cycling and "permanent standing" mode simply by tapping the toe of the device.

7.2.2 Negative aspects of the commercial product's packaging

A negative aspect of the C-Leg® packaging also lies with the compactness of its design. Although the ability to conceal a prosthetic device requires that it be compact, the C-Leg® package produces an unsymmetrical imbalance between the size of the prosthetic and the size of an actual leg when the device is not concealed with a user's lower garment. This imbalance can lead to undesired attention and a perceived state of not being normal as is sought for the user by the prosthetic's manufacturer.

7.2.3 Adapted aspects of the commercial product's packaging

The prosthetic is marketed as a device that can make the user both look and feel as close to normal as possible. The team hopes to adapt the attractive, aesthetic features of the C-Leg® package into their design since they envision it will be used in conjunction with prosthetic devices like the C-Leg®. This necessitates a package that will provide the user the option to either show off the device as a stylish, high-tech accessory or conceal the device thereby preserving Otto Bock's goal to make the user look and feel as close to normal as possible. In order to achieve these features, the packaging must be compact and visually pleasant.

7.2.4 Unique aspects of our project's packaging

The most unique aspect of the project's packaging that differentiates it from the C-Leg® is that it can be interfaced to and used in conjunction with lower limb prosthetic devices like the C-Leg®. The C-Leg® employs many similar technologies found in team nine's product; however, it is packaged as a stand-alone prosthetic device whereas the team's device is packaged most like a prosthetic device accessory. This detail alone provided a unique set of constraints when deciding on the package design. Unlike the C-Leg®, the team was not limited by the significant amount of mechanical constraints that must be addressed when developing a full

prosthetic device that must support the weight of the user. Furthermore, since the team developed the system as an accessory, modularity is an additional constraint in the design. In order to address this, the product packaging was split into four distinct units: two sensor input units, one central processing and display unit, and one sensor output units.

II. Rheo Knee™ by Össur [2]

Figure 2. Rheo Knee™ by Össur

The Rheo Knee™ is a state-of-the-art lower limb bionic device developed by Össur. The device is marketed as a bionic device as opposed to a prosthetic device because of its use of electronics, sensor systems, and artificial intelligence to bring the user "unprecedented natural movement." As can be seen in Figure 2, the packaging of the system does a stellar job at hiding the complexity of the device. The Rheo Knee™ employs a vast array of technology including a dynamic learning algorithm that allows the device to learn a particular user's walking style in order to optimize swing control, a magnetorheological actuator that varies the devices knee resistance in real-time, a microprocessor controlled stance that safeguards against disturbances in the user's path and potential stumbles or falls, and a self-calibrating operating mode.

7.2.5 Positive aspects of the commercial product's packaging

A positive aspect of the Rheo Knee™ package is its discrete design. Like the positive aspect of the C-Leg® package, the Rheo Knee™ can be hidden from others underneath a lower garment, however, the package is also quite effective at concealing potentially intimidating electronics from the user him or herself. Such a complex system could intimidate or brood mistrust in users who know or care little for the technology employed by the bionic device. The

simple, yet effective packaging eliminates the user's need to interact with or regard the innards of the design, allowing a clean human-machine interface.

7.2.6 Negative aspects of the commercial product's packaging

A negative aspect of the Rheo Knee™ package is that it is simply just a knee. Unlike the C-Leg® unit, the Rheo Knee™ is not a full prosthetic device since the prosthetic foot mechanism must be purchased separately. This specification requires that there be an additional connection between the bottom of the knee and the top of the foot mechanism. Although modular systems can often be beneficial, having to construct ones prosthetic from multiple devices, and potentially maintain separate parts of the prosthetic using different methods may be an inconvenience to the user.

7.2.7 Adapted aspects of the commercial product's packaging

A key attractive feature of the Rheo Knee™ package is that it nicely conceals the complexity and technology of the device allowing the user to simply see an object that can help them acquire a better walking experience. The team was able to implement this feature with both its foot pressure sensor system as well as its output vibrating motor system by concealing the complexity of the sub-system designs behind their packaging. The user need only know that they can clip the vibrating motor strap around their leg, and place their prosthetic foot on the foam sensor pad, and it will operate in the way the team and user desire. The team also hopes to employ this feature with their main module design, by creating a simple interface that will allow the user to quickly switch between learning/operating modes without requiring an understanding of how the system works.

7.3 Unique aspects of our project's packaging

The most unique aspect of the project's packaging that differentiates it from the Rheo Knee™ is that it again is a design that can be interface to and used in conjunction with lower limb prosthetics and bionics like the Rheo Knee™. The Rheo Knee™ employs electronics and

sensors to address several significant concerns with regard to correcting a user's gait and aiding a user with "swing control," however much like the C-Leg®, it is packaged as a stand-alone prosthetic/bionic device capable of handling multiple requirements of a safe and stable prosthetic, whereas the project is to be used as an accessory to return the sensation of walking to the user. This facilitates the team's decision to make a compact, lightweight, modular design that can easily be interfaced with a variety of prosthetic/bionic devices.

7.4 *Materials List*

Description	Quantity
7.5" x 4.3" x 2.2" Polycarbonate enclosure [3,4]	1
2.5" Black Strap & Connectors	6
2.5" x 1" Black Cloth	1
Foam Foot Pads	2
Cork Sensor Covers	4
Wire & Input Connectors	6

7.5 *Tooling Requirements*

Minor modifications to the polycarbonate enclosures were done in order to create adequate spacing for the printed circuit board to fit snuggly in the box. This was performed through the use of a milling machine.

7.6 Estimate of Packaging Weight and Unit Cost

-Estimated Package Weight

Description	Est Weight (grams)
Vibrating Motors & Strap	15
Clinometer Sensor & Strap	10
Foot Sensors & Foam Pad Package [5]	5
Total for I/O modules	30
7.5" x 4.3" x 2.2" Polycarbonate enclosure [3,4]	30
Battery	40
PCB Board and components for main module	30
LCD	30
Total for main module	130
Overall Estimated Weight	**160**

7.7 *Estimated Package Cost*

Description	**Price ($)**
7.5” x 4.3” x 2.2” Polycarbonate package [3,4]	7.00
15” Black strap & Clips	5.00
Input/Output connectors & Twisted wire	5.00
Screws and Nuts	1.00
Foam materials [5]	5.50
3M Velcro	3.50
Total	**$ 27.00 / unit**

We estimate that the total packaging weight of both the main processing unit as well as the on-board peripherals is approximately one-hundred and sixty grams, and will cost approximately twenty-seven dollars per unit. We estimate that our overall design costs will be approximately six hundred dollars.

8.0 Schematic Design Considerations

8.1 Introduction

The design is a system that supplements existing prosthetic legs and provides the patient with some sensory feedback about the pressures on the foot through an array of vibrating motors worn on a strap around the thigh. The system will use four small pressure sensors placed in the insole of a shoe and a clinometer at the knee to record information about pressure on the base of the foot and which phase of stride a patient is in. All of the sensor output signals will be interpreted by the microcontroller which uses these inputs to determine where there is pressure on the foot and activates the appropriate motors. The microcontroller will also use non-volatile memory to store statistics about how the patient has been walking and allow it to be uploaded via an Ethernet connection. The system will also use software that will allow the execution of "training programs" in which a light vibration from the motors prompts the patient to make movements and apply pressure in the proper order while they are learning to walk with the prosthetic. To distinguish between modes the microcontroller will also interface with a 16x2 character display that can display mode and other information. A rotary pulse generator will also be interfaced with the microcontroller in order to allow the patient to control the mode of the system. Finally, because the system must be portable it will be battery powered and will display the current battery level on the LCD. This document will detail the dataflow of the design and explain the rationale behind the circuit design.

8.2 Theory of Operation

8.2.1 Pressure Sensors

The Flexiforce® A201 Standard Force & Load Sensors are designed to act as force sensing resistors and are used to detect the pressures in the sole of the shoe. In order to receive an output voltage proportional to the input pressure the manufacture recommends an operational amplifier circuit as shown in the sensor data sheet [1]. This circuit is used as the basis for the pressure sensor amplifier/filters portion of the circuit. The modified circuit also acts as a filter to help reduce noise picked up by the long leads of from the sensors. Filtering is achieved using capacitors whose values were determined through experimentation until noise was sufficiently reduced. The circuit uses a LM324 quad op amp package, which only requires a 7.2V and

ground connection instead of an op amp requiring +9 and -9 V, reducing the number of required supply voltages. Also included in the circuit are potentiometers connected to the op amp outputs to adjust the gain of the circuit.

8.2.2 Clinometer

The Accustar® Electronic Clinometer with radiometric output is designed to act like a potentiometer. It is being used to detect the angle of the lower leg relative to the horizon. It requires a 3-pin connection consisting of signal (output), ground, and a supply voltage of 5V to 15V regulated according to the datasheet [2]. Output resolution is directly proportional to input voltage; however, a supply voltage of 5V is used because it is already required on the circuit board to supply CMOS parts and this choice helps to reduce the number of required power supply voltages in the overall design. While this choice provides less resolution than higher voltages, it is still sufficient for the design. A 5V supply also guarantees that if the circuit is functioning properly, there will never be more than 5 volts output to the microcontroller, which has an absolute maximum input voltage of 6.5V.

8.2.3 Microcontroller

The microcontroller used in the design in the Freescale MC9S12NE64CPV which operates on a supply voltage of 3.3V. The MC9S12NE64 was chosen primarily because it includes 70 I/O pins and an integrated Ethernet controller, which can be used to upload recorded device usage data. The use of this integrated controller requires that the chip operate at 25MHz. This is achieved using a 25MHz crystal oscillator circuit. The basic interface of the microcontroller to the external crystal, RJ45 connector, and background debug mode (BDM) header used for programming is based on the manufacturer recommended circuit shown on page 550 of the datasheet [3], with the addition of a run/load switch on pin 26 to upload programming. The pressure sensor and clinometer output signals are interfaced to the microcontroller through the ATD ports on pins 85-89. An additional ATD port on pin 90 is used to monitor the battery level using a voltage divider to reduce the 7.2V battery level to approximately 1.3V. The vibrating motor outputs are connected to pins 99-100 and 103-108 and will use pulse width

modulation to drive a BJT transistor circuit, which in turn drives the motors. The LCD display will use an 8-bit databus, read/write, and chip enable signals, and will be connected to pins 13, 16-19, 22-25, and 27-19 using general I/O. The last component interfaced to the microcontroller is a rotary pulse generator with a momentary switch that will be used to input user selections into the microcontroller. The RPG has seven pins with two connecting to the microcontroller on general I/O pins 11 and 12 for the RPG and one connecting on pin 10 for the momentary switch. Finally, in addition to interfaces with other components, all of the pins on the microcontroller are connected to 28 pin headers that will surround the chip and allow for easy debugging or easy access to all pins should design changes be necessary.

8.2.4 Motors

The vibrating motor strap used to relay information to the user contains Sanko Electric Vibrating Motors operating at 3V and up to 100mA [4]. In order to meet the current requirement of the motors, BJT amplifier circuits controlled by the microcontroller are used. The amplifiers were designed using resistor values that would cause the transistors to operate in saturation and limit current. Because the amplifiers are connected directly to the microcontroller, Schottky diodes are places across the amplifiers to help protect the microcontroller from current spikes.

8.2.5 LCD

The Crystalfontz CFAH1602A-RGB-JP LCD is used to display mode and battery information and has a 16-pin interface with an 8-bit databus [5]. The LCD module requires a 5V supply voltage for logic and a 3.8V supply voltage for the LCD. Both voltages are drawn from the 5V regulated supply with the 3.8V being achieved through a voltage divider. Non power pins are interfaced to the microcontroller.

8.2.6 Power Supply

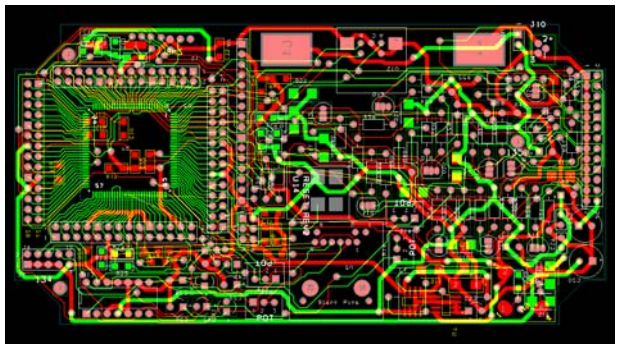
The power supply is built around a 7.2V RC battery because it is a commonly available rechargeable battery with a reasonable charge capacity and provides sufficient voltage. It uses a

LTC1174HV-5 to generate +5V and -5V regulated supplies and a LTC1174-3.3 to generate a 3.3V regulated supply. These regulators were chosen because they are able to supply the required voltages and are able to meet the current requirements of the design. The circuits used are example application circuits shown on pages 16 and 12 of the LTC1174 datasheet [6] under typical applications.

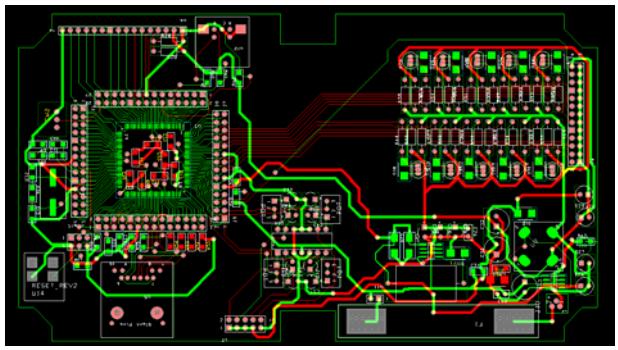
9.0 PCB Layout Design Considerations

9.1 Introduction:

The purpose of this design project has been to build an attachable system for existing prosthetic legs which would allow patient to "feel" the pressure changes under his artificial foot via a vibrating motor strap worn around the remaining appendage. Pressure detection occurs in thin-film pressure sensors located in a sandal which feeds a variable dc voltage to the ATD port on the microcontroller (a HC12 variant) via four integrating amplifiers which provide noise reduction capabilities. Once sensor data management occurs in the microprocessor, PWM signals are generated and delivered to ten class D amplifier circuits consisting of Schottky diodes in parallel with NPN bipolar junction transistors. The power supply for the system generates 5 volt, -5 volt, and 3.3 volt regulated outputs and one unregulated, fused 7.2 volt supply. The switched main power comes from a 7.2 volt remote control car battery which is to be located under the PCB during final installation. During layout, the class D amplifiers, the integrating amplifiers, the power supply, and the microcontroller will all need to be isolated as much as possible on the PCB.



(a) PCB Design for smaller acrylic box: 5"x3"x1.5" (overly-complex version)



(b) PCB Design for larger acrylic box: 7"x4"x2" (cleaner version)

Figure 2.1 - Layout Options for Two Potential PCB Containers

9.2 PCB Layout Design Considerations

In constructing the PCB for the G.I.M.P. system, considerations were made in the areas of electrical, mechanical, and anatomical necessity. Merging the physical dimensions of the actual device, the environmental conditions under which the device is expected to operate and

the corresponding electrical implications given thereby, the PCB was designed to meet all requirements. These design constraints will now be examined in greater detail:

9.3 Physical Constraints on the PCB

As the G.I.M.P. device is intended to be an addable system to existing prosthetic legs, it is exceeding important that the physical dimensions of the device be minimized so that minimal volume is occupied in close proximity to the prosthetic itself. An undesirable design would be one in which the patient had to wear a "box" which was clearly visible through the clothes. The selected container for the PCB has two available sets of internal dimensions [1] for which two individual PCB layouts were designed. One acrylic box occupied approximately 5"x3.5"x1" while the other occupied 7"x4"x1.5". A conceptual image of each PCB layout can be found in Figure 2.1 which illustrates the graphical complexity of each layout option (note: Figure 2.1b does not include the copper pour for understandability purposes. Among the criteria yet to be discussed, one of the most important in selecting our final layout choice was the complexity of the PCB itself. For the smaller of the two boxes, only 90% routing could be completed and over 100 vias were required. For the larger box, only about 50 vias were needed and all routing could was completed efficiently. In this sense, although the larger of the two potential boxes was selected to accommodate our final PCB design, it satisfies the physical constraint of occupying a minimum volume.

As stated, the dimensions of the selected acrylic box are 7"x4"x2", although the internal dimensions are not rectangular but rather reflect the internal construction of the box [1]. As such, the PCB for the G.I.M.P system is outlined by a trace on the global layer (marked by the edge of the copper pour) which follows the shape of the inside of the box, navigating around six posts distributed throughout the box. The PCB will be mounted to the case itself with metal separators and bolts mounted through the bottom of the box. Four mounting holes were added to the PCB to accommodate these requirements. As the internal depth of the box is 2", it was necessary that the PCB be designed to require no greater depth. As the two largest components for the PCB were the 50uH inductor and RJ-45 connector, the sum of these to thicknesses determined the maximum width of the board if both sides were populated. The thickness of these components is less than 1.5", and so it was determined that both sides of the PCB could be

populated while leaving ample room inside of the case for jumper cables to the motor strap, sensor array, and battery. Figure 2 illustrates the width considerations for the PCB.

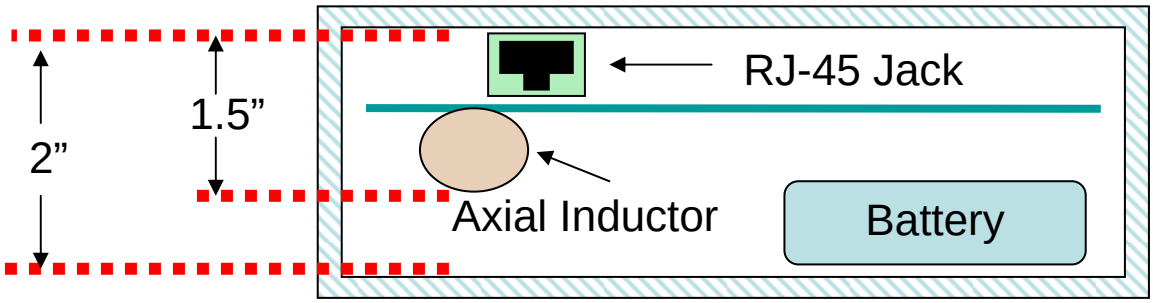


Figure 2 – Width considerations for PCB Layout

It must be assumed that the PCB will be subjected to the same environmental conditions that a human leg would be subjected to throughout the course of daily life. While the acrylic box will provide ample isolation between the electronics and the surrounding environment, all electronics will be subject to the same electrical conditions that the patient may experience. For this reason, a copper pour was added to the top and bottom layers of the PCB to aid in grounding any EMI that may come from the environment (for instance, if the patient drags his feet along turf and generates significant charge).

9.4 Electrical Constraints for the PCB

Due to the close proximity of the digital and analog components imposed by our packaging constraints, it was very important that there be maximal isolation between components located within a small area. For this reason, it was chosen that a copper pour be added to both sides of the board which, while typically used for isolation in circuits using RF components [2], would also provide isolation between the class D amplifiers (located on the right of the board) and the microcontroller (located on the far left). Because the class D amplifiers operate with a variable pulse in the form of a square wave, it was noticed that there may be significant noise in the high frequency components which make up the square wave. While these noise components would have little effect on the robust digital circuitry, the analog to digital converters for the foot pressure sensors could be affected. For this reason, it was decided that the ATD circuitry (consisting primarily of a quad op amp, four potentiometers, and several

capacitors) be located as close to the microcontroller as possible as to minimize the distance between the ATD amplifier outputs and the actual ATD ports on the HC12. The same strategy was taken with our clock and bypass capacitors which are also located directly next to and under the microcontroller respectively.

Another concern, also related to the ATD circuitry is the long "artificial ground" lines feeding into the four op-amps. Because the operation of the op amp involves the amplification of a voltage difference between the inverting and non-inverting inputs, any noise on the ground line (which runs all the way down to the foot) would be amplified prior to being fed into the HC12's ATD. To minimize noise along these ground lines, copper foil was placed around the sensors themselves, and coiled-pair wires lead between the headers on the PCB to the sensors. When tested with various sources of noise in the lab (e.g. switching sparks), the measures taken were shown to be highly affective and what little noise could not be compensated for through PCB layout techniques would not be sufficient to affect to operation of the overall device.

Trace sizing was determined on the amount of current which was anticipated to be passed through each wire in a given net. For all digital circuitry, no more than a few milliamps would be passed into or out of the microcontroller and, for this reason, 12 mil tracing was used with the exception of the lines leading from the headers into the microcontroller itself which were chosen to be 8 mils. An 8 mil trace can handle currents on the orders of a couple hundred milliamps (this number varies with the material used for the trace, the thickness of the trace, and the temperature of operation)[3]. The thickest traces on the board are the 40 mil power traces. If all circuitry is being powered (including all 10 motors which draw about 100 milliamps each), no more that 1.5 amps will be drawn across any power rail. 40 mil traces are rated to approximately 1.8 amps [3] and were deemed sufficient for our design. To protect against current spikes, a fuse was added to the power supply to ensure safe operation (more precisely, electrical isolation of the supply power in the event of a surge in current) above the rating for the power traces.

It should be noted that through-hole parts were chosen for all analog circuits including the class D amplifiers for ease of installation and for testing purposes (through-hole parts provide affective testing points). To provide the same capabilities around the microcontroller, all microcontroller pins have been wired directly to headers. Should the PCB be manufactured during post-development, it should be noted that ample volume would be saved if these headers were omitted and only surface-mount components were used.

Any footprints which were not readily available in existing libraries were generated directly from the manufacturer specifications. The components included the RPG, RJ-45 jack, Power and Run/Boot switches, fuse, power jack, and reset pushbutton. Before the PCB was sent out for manufacturing, all components were "tested" against the generated footprints. No errors were observed.

10.0 Software Design Considerations

The microcontroller chosen for our project is the MC9S12NE64CPV (NE64). The NE64 uses the CodeWarrior compiler that allows programming of the micro to be done in C. Freescale offers some free C code for use with the NE64 [2] which we have used for the basis of our program (register and port initializations, etc.) and into which we have inserted our own code for our core software modules.

10.1 Memory Model

The NE64 has 64 KB of programmable, non-volatile Flash memory and 8 KB of volatile SRAM. We anticipate the Flash being more than sufficient for amount of code storage that will be needed, but the 8KB of SRAM was a cause for some concern and caused a small modification in how we planned on using the Ethernet capabilities. Originally, we had considered recording sensor input data while the user is at home for some period and storing this information in SRAM to later be uploaded at the doctor's office. Because the size of the SRAM is so limited, however, the patient will do his or her sample walking at the doctor's office (either on a treadmill or around the room if the cord is long enough) and the data will be uploaded through the Ethernet while it is being recorded.

10.2 Memory Map

The memory for the NE64 is mapped as follows[1]:

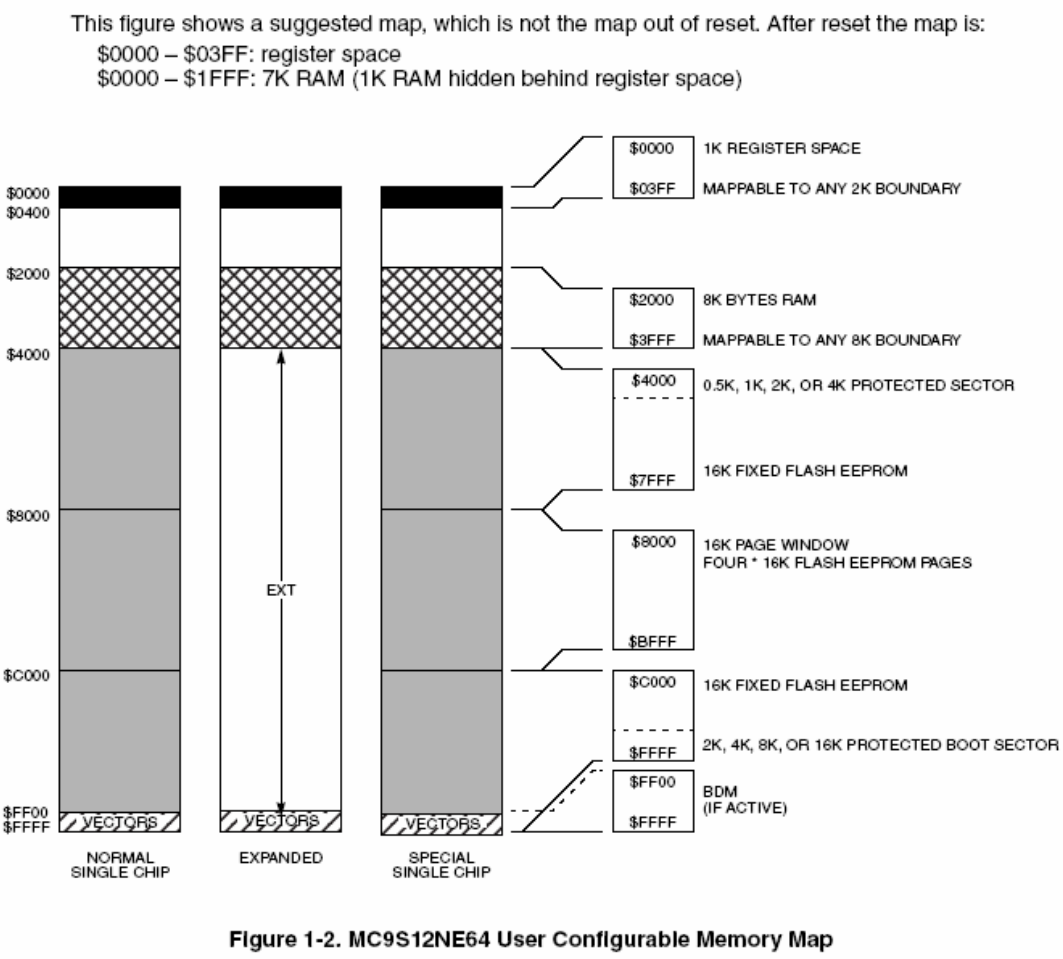


Figure 1-2. MC9S12NE64 User Configurable Memory Map

The 8K of RAM in Figure 1-2 above is a volatile portion of memory where variables are stored, while 16K sections of fixed Flash EEPROM are non-volatile and store the actual code that are programmed into the microcontroller.

10.3 Startup Code

Startup code is already provided within the OpenTCP C code we are using as the basis for the code for our project [1]. On a cold boot, _premain() and then main() will be called. In addition, this startup code will automatically be called on a chip reset. We have modified this main() function to include the initialization of I/O ports as well as the ATD and hardware interrupts (for Pulse-Width Modulation). The LCD screen is also initialized on startup.

10.4 Organization of Embedded Application Code

The code for our project is best categorized as loop driven. The major functionality of our project involves continuously polling the sensory inputs on several ATD ports, interpreting the data, and then driving the motors in the motor strap accordingly. In direct-mapping mode, for example, our system will continuously monitor the pressure sensors. When a sensor detects a certain amount of pressure it will drive the corresponding motor(s). The Motor Output module initially "drives" each of the ten motors with a 0% duty cycle, which results in no vibration. Duty cycle then changes to 100% when particular sensory input data is received.

10.5 Software Design Narrative

The code for this project can be broken up into seven primary modules: Main/Startup, Liquid Crystal Display (LCD), Analog-to-Digital Sensor Inputs (ATD), Sensor Data Management (SDM), Motor Output, Power Conservation (ATD + Battery Monitor), and Ethernet.

10.5.1 Main/Startup

This module was touched on earlier in the report. After some initial code is executed at startup or reset, main() is called. Main() handles the initialization of I/O ports as well as the ATD, hardware interrupts (for Pulse-Width Modulation), and modules. These initializations consist only of setting control registers to activate the built in modules on the chip. The LCD screen is also initialized on startup. Our code for initializing the LCD was adapted from [3] using knowledge we acquired from [4].

10.5.2 Liquid Crystal Display (LCD)

The LCD is initialized in the main() function, and as mentioned was adapted from published code [3] to accomplish this. Timer interrupts were used to fit the timing characteristics of the LCD during initialization. The same source also included code to display characters on our LCD, which was adapted for our purposes.

10.5.3 Analog-to-Digital (ATD)

ATD capabilities are built into the NE64 and are quite simple to utilize. The ATD is initialized by setting control registers to select bit precision, among other things. 8-bit precision was chosen, which more than satisfied the needs for this project. This is used to measure the force being exerted onto each of the pressure sensors, as well as to measure the angle of the patient's leg, which is measured by the clinometer.

10.5.4 Sensor Data Management (SDM)

SDM is the next step after the ATD sensory input. In this module, the input from the ATD is fed into a lookup table which determines whether the sensor input values are above the required threshold. In direct mapping mode, the table entry will refer to which motors must be driven when the sensors are determined to be at particular values. In the training mode, however, this lookup table will be used in a slightly different way. This time, there will be an expected pressure/angle value that will be compared against the actual value of the sensor inputs provided when the user is walking. If the expected value is met, the next stage of Training is entered.

10.5.5 Motor Outputs

10 motors can be driven at separate times according to the sensory input data through the ATD. In Direct Mapping mode, when the ATD inputs are determined to be over a specific threshold value, the appropriate motors are driven in the vibrating motor strap. This is done by simply setting the correct output ports. In Training mode, on the other hand, specific motor "instructions" are given (again by setting the appropriate output ports), and when the expected sensory values are satisfied, the device moves to the next stage of the training process. A flowchart describing the function of the Direct Mapping and Training Modes is provided in Figure 2 below.

10.5.6 Power Conservation

The Power Conservation mode in our system will also be run using the ATD module. There are two things that cause the prosthetic to enter Power Conservation mode. The first occurs if the battery is low (this is measured by simply the voltage output of the battery being put

into an ATD channel). The second occurs if the prosthetic has been idle for a specified amount of time (if the user is standing in place, enough pressure is exerted on the sensors to prevent the device from entering the idle state). To determine when the device is idle, a global counter is added which increments every time the ATD detects no sensor input, and then clears again when the ATD does change. After the counter has reached a value that is sufficiently high, the prosthetic will enter into power conservation mode. An RPG button press will wake the system up from this idle mode. Battery-level induced power conservation mode, however, will not wake up when you touch the RPG. A new battery is needed and the system will not be restored to full strength without one.

10.5.7 Ethernet

The Ethernet module is built in to the NE64 and is a big reason we chose this particular MCU in the first place. Since there is only one-way data transfer this module is not expected to be a terribly difficult module to implement. It is, however, also the one we know the least about.

10.6 Software Documentation

This section will use flowcharts to explain how the modules will be implemented, and also includes a list of functions with a short description of how each works.

Figure 10. 2: Direct Map and Training Modes Flowchart

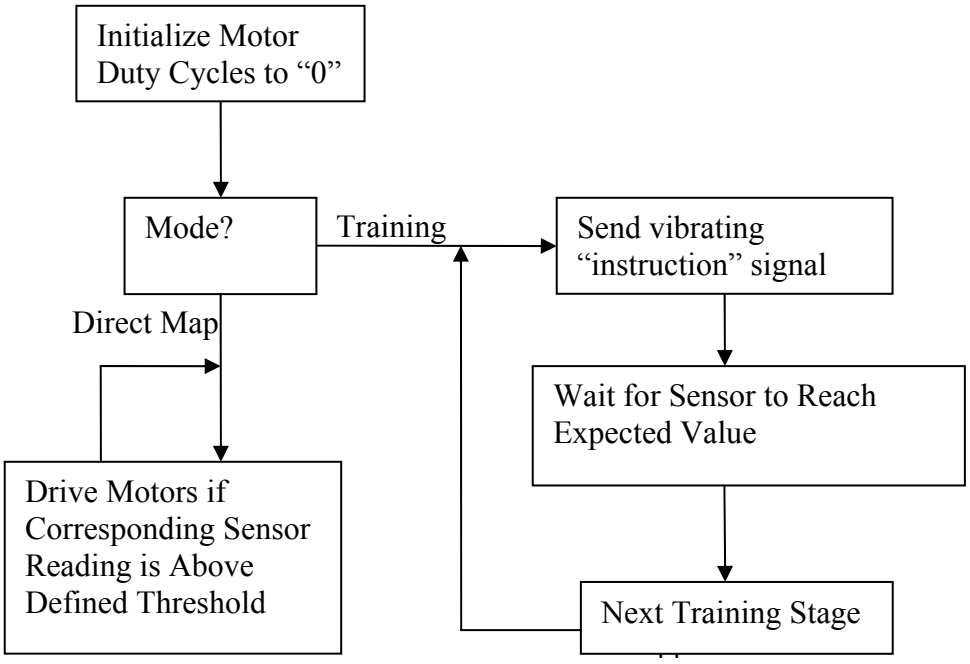

Initialize Motor Duty Cycles to "0"
Mode?
Training
Send vibrating "instruction" signal
Direct Map
Wait for Sensor to Reach Expected Value
Drive Motors if Corresponding Sensor Reading is Above Defined Threshold
Next Training Stage

Table 10.1: Function List

Function Name	Comments / Description
void main()	Initializes ATD, Motor Output, LCD, and I/O pin directions
void LCD_WriteString(char[] String, int Line)	Writes the string passed to this function onto either the first or second line of the LCD
void Power_Down(int Low_Battery)	Puts the system into conservation mode. Low_Battery indicates the reason for the Power_Down and determines whether an RPG push button will wake the system up or not (if Low_Battery don't wake up)
int Send_Packet(struct Packet *Ready)	Sends the packet pointed to by *Packet to the doctor's computer via an Ethernet cable. Returns 0 on success.
int Get_Closest(int Value)	Returns the closest value that will match a table lookup value. In reality this just takes Value and removes some of its precision.
int Motor_Lookup(int Value)	Samples all the ATD ports and drives the motors accordingly
int ATD_Value(int Sensor_Num)	Returns the ATD input of the sensor indicated.

11.0 Version 2 Changes

The most important "second iteration" change would be the size of the device itself. Currently, the G.I.M.P. system's control module occupies 7.5"x4.3"x2.5" which is far too large to be functionally used by a patient. Optimally, if the device could be condensed to approximately the size of a cellular telephone, it could be easily implemented into existing prosthetic legs without making a bulge in the patent's clothing as is currently the case. In order to condense the size of the unit, test points, power LEDs, and internal "development hardware" like the BDM jack and run/boot switch should be removed from the schematic. Also, it is recommended that the second iteration use only surface mount parts so as to minimize volume occupied by the PCB.

In the motor strap, the LEDs could be removed as they do not provide functional feedback to the user but were, instead, intended to assist in the software development process. This would affectively reduce the diameter of the motor strap, reduce weight, and drastically reduce power consumption during device operation. In its first iteration, the G.I.M.P. system uses and LCD whose backlight is always on. Although visually attractive, the bright red LCD backlight consumes significant power and it is for this reason that a LCD be used in future iterations which occupies less power and includes an interface to the microcontroller which allows for the backlight to be turned on and off through software (thus providing the same type of functionality offered by many digital watches).

Having a RAM chip interfaced to the microcontroller in future iterations would allow for the execution of more complex programs as bio-statistical information could be recorded externally and not on the microcontroller's internal Flash. It is believed that about 64K of external memory would be more than enough to provide this functionality, although an SD card could also be used which would provide an additional means of data transfer from patient to doctor. If data management was improved and more complex programs could be executed on the microcontroller, higher resolution sensors and motor configuration could be implemented which would provide the user more distinct mappings of pressures on the bottom of the prosthetic to vibrations around the thigh.

It is believed that sound feedback for the LCD would provide ample assistance to a user when selecting a mode. A simple click would provide this functionality which could be implemented through a simple single-tone speaker. Finally, a more compact clinometer would

be easier to integrate into existing prosthetic devices and would reduce the G.I.M.P. system's overall weight.

12.0 Summary and Conclusions

During the completion of this project, the General Informative Medical Prosthetic system was designed and constructed with the goal of communicating pressures on the bottom of a prosthetic foot to unique vibrating patterns around the upper appendage via vibrating motors. In the process of completing this project, analysis was done on design constraints, safety and reliability, environmental impact, and patent liability. Several technical accomplishments were made including the design, layout, and population of a PCB and all peripheral devices which interfaced to it (foot sensors, vibrating motor strap, clinometer sensor, rotary pulse generator, and LCD). All steps in the design process were well documented in online journal entries and all five success criteria were met and videotaped at the conclusion of the project.

Many important lessons were learned during the completion of the G.I.M.P. project for ECE 477. Firstly, it is exceedingly important to start acquiring parts as early as possible. Circuits cannot be properly bread boarded until all circuits are in hand, and the final project proposal should not be constructed until all "proposed" circuits have been tested. This means that, almost immediately, ECE 477 teams should be purchasing parts and having them shipped. The generation of OrCad layout and capture files takes about three times longer than expected and so this process should also be started very early. As "all-nighters" are inevitable for this type of project, it is generally a good idea if they are had toward the beginning of the project so that completion of the success criteria is not endangered. Understanding the software development should take place in parallel with the development of circuits. The process of learning a software package can take up to two weeks for ECE477. When designing the PCB, it was determined that multiple revisions are necessary; the first revision should be designed to fit onto the smallest PCB possible with subsequent revisions gradually increasing the PCB's area until a practical set of dimensions is determined.

In general, it is a good idea to come to ECE477 with project ideas and teammates in hand. This, in essence, saves about a week at the beginning of the semester which can be used to search for parts and begin on initial circuit bread boarding. As both hardware and software are critical elements of the G.I.M.P. system, it was determined that having both disciplines of electrical engineering and computer engineering represented on the team is absolutely critical. The project would not have come together correctly if both sides were not represented. The mutual responsibility of group members is vital since no one person can truly understand every aspect of

how the project works. It is important to each member of the team to take ownership of a particular part of the project and put effort into communicating the *interfaces* of that particular component to the rest of the team's members. System-level design is truly dependent on interfaces, as was the case with the G.I.M.P. system. Finally, some socialization among group members is very important as it prevents arguments from turning into serious conflicts. When certain periods of development become notably stressful, taking time to recognize the human aspects in group dynamics is a vital element to the group's overall success.

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Appendix A: Individual Contributions

A.1 Contributions of Jeff Huston:

Jeff Huston made the majority of his contributions to the project in the area of software development. The major software modules that were developed by Jeff were the PWM Module for motor output (shared with Omar Shaikh), Sensor Data Management, the ATD Module for sensor input, the Idle Detection Module, the Rotary Pulse Generator for mode selection and the main code for the Direct Mapping, Training and Power Down modes of the device.

Significant time was spent coding the modules needed for motor output, including the PWM Module and Sensor Data Management. The original design allowed for variable duty cycles for each motor, which required the use of interrupts and a lookup table for translation of sensor data into the desired duty cycle for each motor to be driven. This was later simplified, however, when after some testing of the feedback motor strap it was determined that driving the motors with a 100% duty cycle would increase the user's ability to determine the difference between the discrete vibrating patterns of the motor strap. Driving the motors with a 100% duty cycle eliminated the need for interrupts in this module and also limited the Sensor Data Management to just one 16-bit variable that keeps track of which motors are being driven at a particular time.

The ATD Module was used to measure the input from each of the four foot pressure sensors, the tilt sensor (clinometer), the battery level and the Rotary Pulse Generator. The code for this module involved setting registers to the proper values and determining the proper voltage thresholds being read in from the sensors at which to vibrate the appropriate motors.

The Rotary Pulse Generator has three ports fed into the ATD on the micro, two of which pulse when the RPG is turned and the other which pulses on a button press. This RPG Module samples those three ports with the ATD and is used to toggle between modes on the device.

While timer interrupts are no longer being used to run the PWM Module, they were still required for the Idle Detection Module. When no sensors have been depressed and the RPG has not been toggled for a specified amount of time, the device will automatically go into a Power Down mode to conserve battery. This is done with a counter that is restarted every time no sensor data is being read in.

Jeff also wrote the main code for the Direct Mapping, Training and Power Down modes for the device. The Direct Mapping modes sampled the ATD ports for the pressure sensors in the foot and vibrated the appropriate motors when each sensor crossed a certain voltage threshold. The Training mode on the other hand vibrates certain motors which act as instructions to the user regarding how to proceed with their next walking step. When the desired pressure sensor (and tilt sensor) levels are achieved, those particular motors will stop vibrating and a different combination of motors will then start vibrating to instruct the user to proceed to the next step in the walking process. The result is a four-stage walking instruction process. The Power Down mode is entered when either the prosthetic is idle or the battery is low, and turns off the ATD conversion and interrupts, which results in conservation of battery life.

A.2 Contributions of Ryan Koors:

Ryan Koors worked primarily on the hardware and packaging of the design. He completed the constraint analysis of the design and wrote the report on the circuit schematic and theory of operation. At the beginning of the semester, he assisted as the entire team searched for the main components of the design including the sensors, motors and microcontroller. Once the motors and clinometer had been obtained, he was involved as the team worked to construct the motor and LED packages that would later be placed in the vibrating motor feedback strap. He also helped make the cloth strap that held the motors and the strap the held the clinometer. He was also able to have the strap for the motors sewn to hold the motors in place. Once initial motor and sensor circuits had been breadboarded, he began to keep track of all the components that would be required in the final design and their respective schematic part numbers in a spreadsheet. This spreadsheet proved especially useful later as it was expanded with part availability, order status, and later PCB footprints. He was involved in creating the microcontroller interface schematic based on the manufacturer's recommended circuit and interfacing the microcontroller with additional peripherals. When the schematic was complete, he found footprints for components with existing footprints in the Orcad libraries and found the datasheets necessary to create footprints for the remaining components. He was involved initially with creating the 5" x 3" board layout, but when it became apparent that completing that size layout might be impossible, he began routing a larger size board while a final effort was

made to finish the smaller board. During layout, he also recognized errors in the schematic and saw that they were corrected which in the end may have helped keep fly wiring of the final PCB to a minimum. After the PCB was manufactured, Ryan assisted Nathan as he soldered the components to the board. He spent a significant amount of time creating cables for things such as the power switch, sensors, clinometer, and motors. Much of this time was spent ensuring that these cables made secure connections and did not contain any shorts between lines that might result in damage to components or malfunctioning of components. Once hardware construction was essentially complete, he continued to debug hardware problems that arose during the software development. He also continued to make minor additions to the packaging of the design. He added Velcro straps inside the plastic box housing the battery to keep it from moving while the device was in use and coming in contact with the PCB. He also added a plastic knob to the RPG to give it a more finished appearance. He wrote much of the user manual based on conversations among all of the team members and revised it based on the teams input. Finally, for the final presentation, he videotaped several of the success criteria videos and edited all of the videos so they would fit within the time constraints of the presentation.

A.3 Contributions of Omar Shaikh:

Group Nine member Omar Shaikh was primarily responsible for software design and development along with Jeff Huston and developing and maintaining the website. A large focus was placed on first structuring the software design and development process for the product using a top-down methodology in order to determine key components and prioritize module development. The main components Omar volunteered to design and develop included the liquid crystal display (LCD) and Ethernet modules to complete two of the five success criteria.

After deciding on the HC12 variant MC9S12NE64 from Freescale, Omar and Jeff began to experiment with the CodeWarrior development software provided with the microcontroller and determined that it would be best to develop the software using embedded C. Omar first evaluated the feature to use Processor Expert, a graphical user interface (GUI) to auto-code specific modules. He decided that it would be best not to pursue using Processor Expert due to software-based limitations and a lack of sufficient documentation to understand with confidence

how it worked. Omar then spent significant time reviewing sample code for the NE64 provided with the demonstration board and off the Freescale website in order to analyze fully working projects as models for development of code for the product.

After becoming accustomed to the coding environment, Omar began development of simple modules to learn how interrupts and analog-to-digital (ATD) conversions were performed on the microcontroller. Both systems of the microcontroller were essential for I/O operations of the product including motor output and pressure sensor and battery input, all of which were directly involved in the remaining three success criteria. He designed and implemented the first method used to generate pulse-width modulated signals to drive the output motors at different strengths using interrupts. He also designed and implemented the first method to perform voltage threshold detection using the ATD converters. Omar then delivered his findings and understanding of the interrupt and ATD systems to Jeff for core module development.

At this point, all code had been developed to program into the microcontroller using a serial port. Omar shifted his focus to determine how to alter the data flow process in order to implement in-circuit programming with the BDM port. This took quite a bit of time due to differences in how CodeWarrior initialized new NE64 projects using a BDM to program the microcontroller and how sample code intended for programming with the serial port were written. Both sets used different library files which made understanding where to find particular function prototypes, register global variables, and vector addresses significantly more confusing. Omar decided that it would be best to shift all development into an existing sample project intended to demonstrate Ethernet use with the NE64 since it was developed for programming with both ports. This method worked well and components of the sample code's structure were used as a base in the final product.

Omar then transitioned to developing the LCD subroutines. Development began with simple initialization code for the LCD, however after burning one LCD, Omar decided it might be safer to consult sample code written for LCDs. One reference for LCD initialization in embedded C for another HC12 variant microcontroller was translated for use with the NE64. This method initialized the LCD for 4-bit mode, so Omar made additional changes and wrote multiple text manipulation functions for 8-bit mode. The code was altered for use with the

printed-circuit board (PCB) microcontroller but the LCD did not work. A review of the hardware lead Omar to the realization that although the microcontroller header pins showed the correct outputs the LCD header did not. He then reviewed the schematic and found that a single LCD output from the microcontroller was routed to two LCD header pins causing the failure. After fly-wiring the PCB the LCD worked as expected.

A significant amount of the Ethernet code was already developed by the provided sample code. The biggest challenge was that the sample code implemented a web server to host static web-pages hard-coded into the Flash memory and the product required the web server to host dynamic information regarding device usage. Omar reviewed documentation on how the Ethernet module was implemented using OpenTCP and modified several of the provided functions to display dynamic information calculated in the main module of the product code. A significant challenge Omar did not have time to overcome was being able to send more information than the Ethernet buffer limitation, which is why only very basic information is displayed. Lastly, Omar added the Upload mode to the main module and modified the Ethernet and TCP initialization functions for use with the remainder of the product code.

A.4 Contributions of Nathan Smith:

In addition to being the administrative lead for Team 9, Nathan focused primarily on hardware and circuit design for the G.I.M.P. system. The original idea for the project was Nathan's before the commencement of ECE477 and he (along with Omar) were responsible for finding other individuals who were interested in the project idea. From the first week of class, Nathan took the lead on compiling the preliminary and final proposal for the team, including the specific wording of Team 9's success criteria. The preliminary proposal PowerPoint presentation was generated by Nathan (including the complex animations which were complemented during the presentation). Although Ryan was responsible for the write up for the schematic, Nathan was the one who designed, bread-boarded, and generated OrCad capture files for *all* circuits in the G.I.M.P. system. Nathan was in charge of the Class D amplifiers (used by the vibrating motors) and the AC noise suppression amplifiers (used by the foot pressure sensors), both of which he designed and tested himself.

A mutual effort between Nathan and Jeff went into selecting and purchasing the parts with which the PCB was later populated. Specifically, Nathan generated the requirements for the parts needed (as he was the lead circuit designer), and these specifications were then passed to Ryan who recorded them in a comprehensive Excel document. Nathan and Ryan then searched for parts online while, all the while, updating the Excel document with the footprints for each part and indicators for parts which needed custom footprints. Once all of the parts had been selected and ordered, Nathan designed all required footprints in OrCad Layout before importing them and the previously created netlist files into the OrCad environment.

Nathan was responsible for approximately half of the final OrCad layout, although he generated the first revision which was later not used due to abscess complexity (the size of the board was increased in the second revision and all traces were re-drawn using fewer vias). Nathan spent over 48 hours designing the PCB layout for the G.I.M.P. system and, as a result of this huge effort, the operational PCB only needed three fly wires. Because he started on the task of generating the layout files so early in the semester, Nathan often help members of other groups to design footprints, choose appropriate components, and avoid errors in OrCad Layout.

When the PCB came in Nathan was exclusively responsible for populating it. Two weeks before this time period, Nathan was practicing soldering fine pitch surface-mounted parts and, as a result, he soldered the 112-pin (12 pitch) IC on himself in one try. Team 9 only used one microcontroller in the entire development process as a result of Nathan's acquired expertise in soldering. Before he proceeded to installing the digital components of the board, Nathan assembled all peripheral circuits, tested them, and made all corrections as necessary. For instance, he determined that pins on the NPN transistors for the Class D amplifiers were switched. Nathan was also in charge of machining the control unit's box (an effort which took several days) and he made sure that the system was as modular as possible so that it could be assembled and disassembled easily. The cables used for connecting the LCD, motor strap, and foot sensors were all built by Nathan before being analyzed by Ryan for short circuits. Throughout the software development process, Nathan remained the lead for all hardware components meaning that, as modules were being developed for PWM and ATD, Nathan was responsible for hooking the device up to the appropriate equipment. The "on-device" software development process was possible because of Nathan's assurance of correct hardware operation. Nathan scored in the high 90s on both of this homework assignments (OrCad Layout and Patent

Liability Analysis) and often took time to peer edit the homeworks of the other members of Team 9.

From the first weeks of the semester, Nathan made sure that Team 9 met on a regular basis by contacting his teammates to setup work sessions. He often showed up to these meetings at least an hour early to get a head start on the day's tasks. Toward the end of the semester, Nathan took charge of creating the Poster, the final PowerPoint presentation, the Senior Design Report, and the Final Project Report (Ryan did the video editing). Although his administrative role in Team 9 was very predominant, Nathan also represented the electrical engineering aspects of the project on a team with three computer engineers. He brought knowledge from ECE 433 and ECE 440 to the project which, combined with the programming skill of his fellows, produced a fully functional system and accomplished the main goal of the class.

Appendix B: Packaging

Figure B.1 Constructed Tilt Sensor and Sensor Output package

Figure B.2 Constructed Tilt Sensor and Sensor Output package

Figure B.3 Constructed Foot Pressure Sensor Package and Test Sandal

Figure B.4 Constructed Foot Pressure Sensor Package and Test Sandal

Figure B.5 Total Constructed G.I.M.P. System

Appendix C: Schematic

Figure C.1 Microcontroller Headers

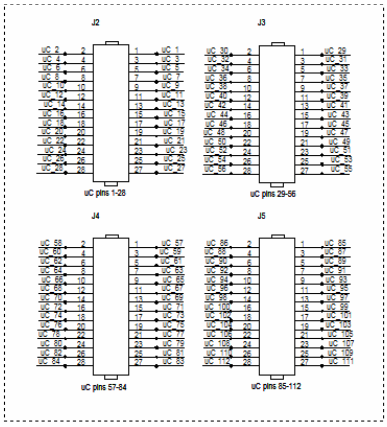


Figure C.2 Motor and Clinometer Header

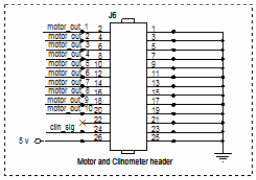


Figure C.3 MC9S12NE64CPV Microcontroller Module

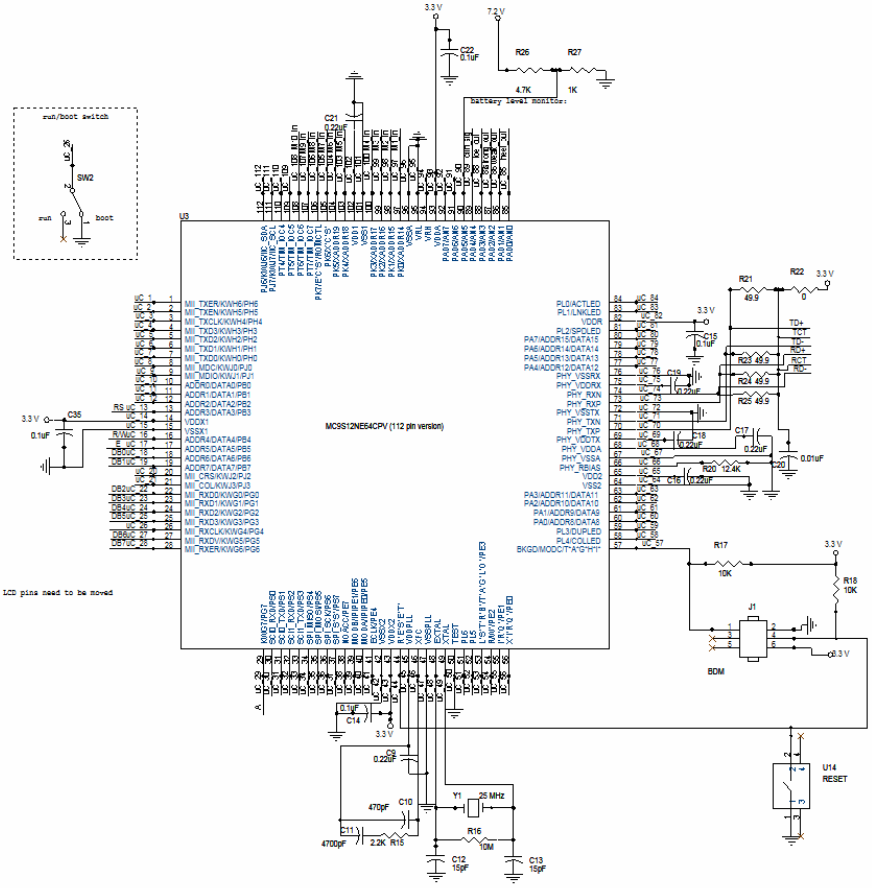


Figure C.4 Pressure Sensors Header

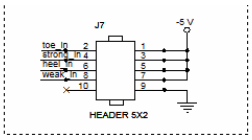


Figure C.5 RJ45 Connector

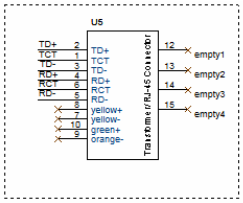


Figure C.6 LCD Header

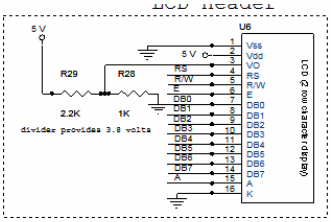


Figure C.7 Rotary Pulse Generator

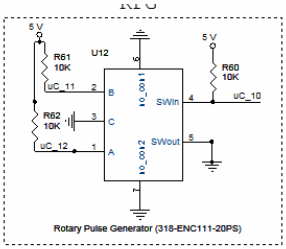


Figure C.8 Power Supply

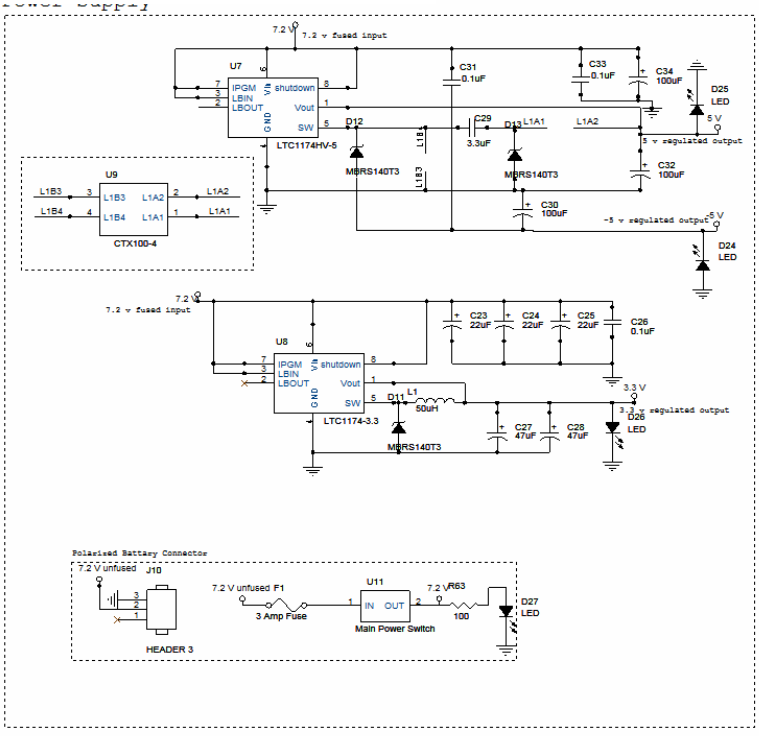


Figure C.9 Class D Motor Amplifiers

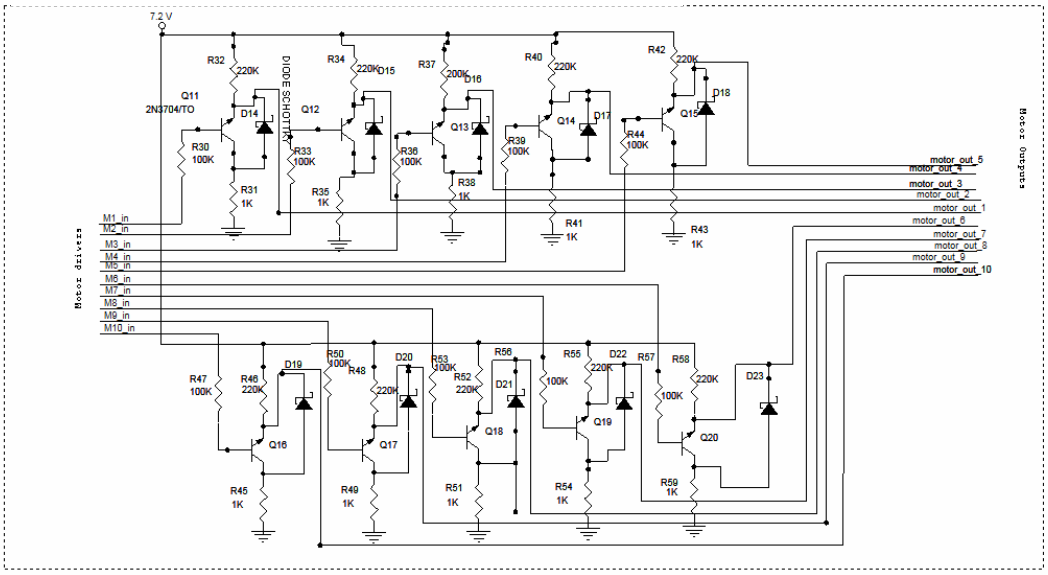
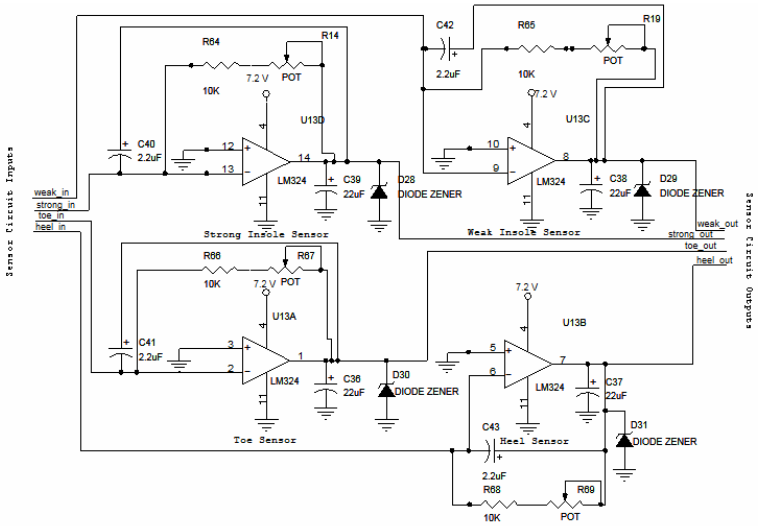


Figure C.10 Pressure Sensor Amplifier/ Filters



Appendix D: PCB Layout Top and Bottom Copper

Figure D.1 Board Top (dimensions: 7”x4”)

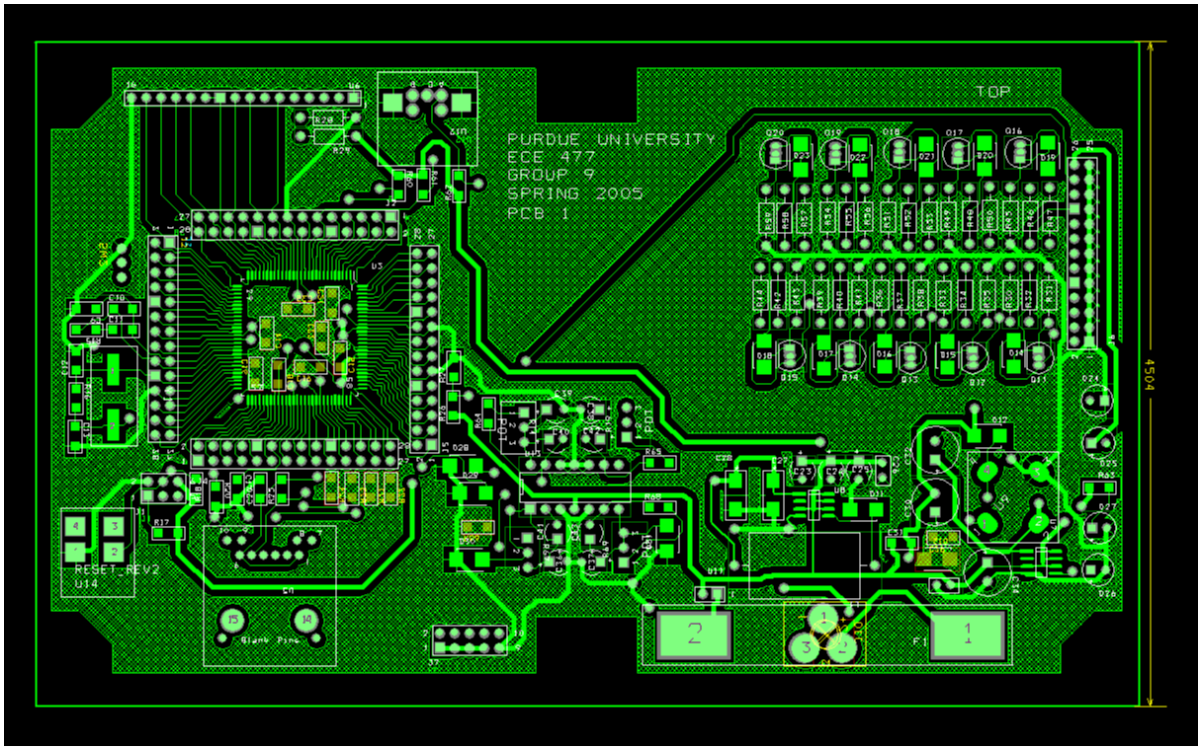
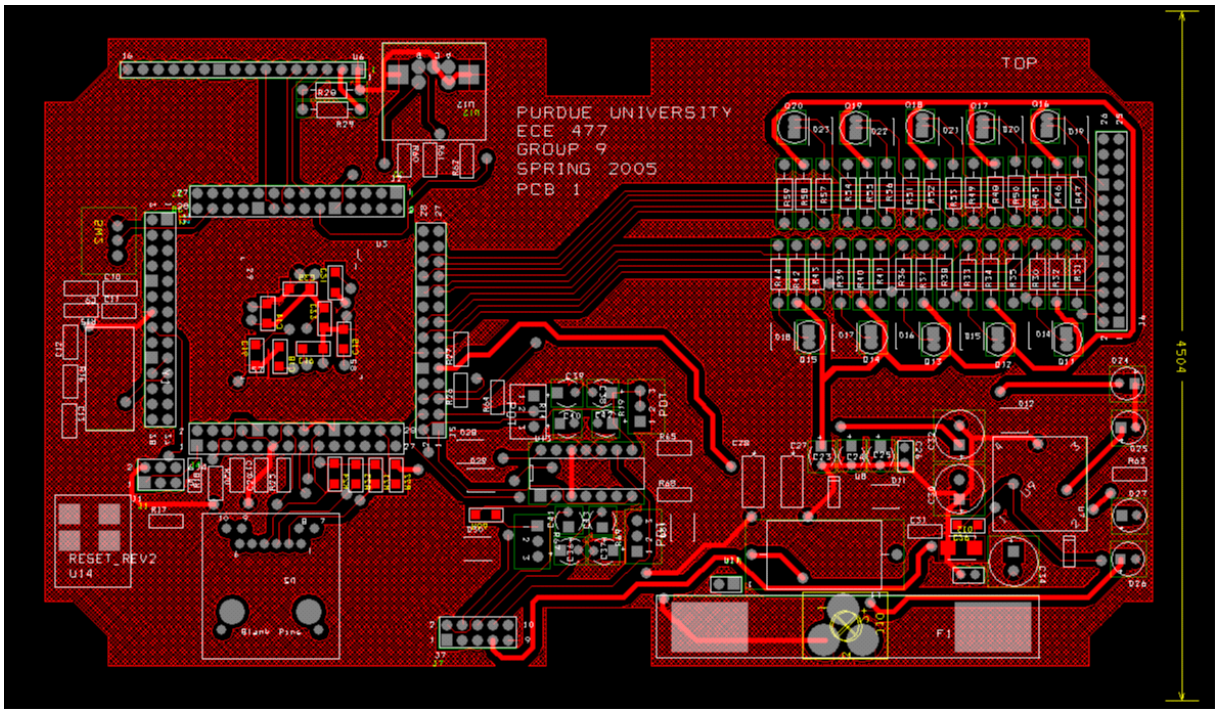


Figure D.2 Board Bottom (dimensions: 7”x4”)



Appendix E: Parts List Spreadsheet

Description	Vendor	Part Number	Unit Cost	Quantity	Total Cost
FLEXIFORCE SENSORS	Tekscan	A201-100	$13.75	4	$55.00
SENSOR CLINOMETER HORIZONTL FLNG	AccuStar	02110102-000	$139.00	1	$139.00
VIBRATING MOTORS	Sanco Electric	1E120	$1.25	10	$12.50
MC9S12NE64V1	freescale semiconductor	MC9S12NE64CPV	$0.00	1	$0.00
16x2 Positive Transflective Red LED Array Backlit LCD Module	Crystalfontz	CFAH1602A-RGB-JP	$12.11	1	$12.11
RJ-45 Connector	Bel Fuse	0810-1X1T-03	$3.93	1	$3.93
Power Regulator	Linear Technology	LTC1174-3.3	$6.88	1	$6.88
Power Regulator	Linear Technology	LTC1174-5	$7.88	1	$7.88
Transformer	Cooper Bussman	CTX100-4	$6.57	1	$6.57
Slide Switch	E-Switch	EG1218	$0.62	1	$0.62
Rotary Pulse Generator	Alpha	318-ENC111-20PS	$4.99	1	$4.99
25 MHz Crystal	ECS Inc.	ECS-250-18-5P-F-TR	$0.73	1	$0.73

Appendix F: Software Listing

Code References:

LCD Reference Source:
Valvano, Jonathan W. MC68HC812A4 Programs
http://www.ece.utexas.edu/~valvano/programs/index.html
Examples accompany the books
"Embedded Microcomputer Systems: Real Time Interfacing", Brooks-Cole, copyright (c) 2000,
"Introduction to Embedded Microcomputer Systems: Motorola 6811 and 6812 Simulation", Brooks-Cole,
Copyright (C) 2002

Copyright 2004 by Jonathan W. Valvano, valvano@mail.utexas.edu

Ethernet Reference Source:
Web Server Development with MC9S12NE64 and OpenTCP
Reference Material: http://www.freescale.com/files/microcontrollers/doc/app_note/AN2836.pdf
Reference Code: http://www.freescale.com/files/microcontrollers/doc/app_note/AN2836SW.zip

http://www.opentcp.org

Copyright (C) 2003 Freescale Semiconductor, Inc. and 2000-2002 Viola Systems Ltd.
All Rights Reserved

Initial Reference Source:
ATD, Timer Channels, Startup, and Interrupt Reference

Startup Demo Test
https://www.freescale.com/webapp/Download?colCode=MC9S12NE64TEST&prodCode=DEMO9S12NE64&nodeId=0162468636K100&appType=license&location=psp
Author (partial): Teri Cheng
Copyright (C) 2003 Freescale Semiconductor, Inc.
All Rights Reserved

```
//=============================================================
/* main */
//
//  - Loop driven structure
//=============================================================
void main(void)
{
//----------------------//
// VARIABLE DECLARATIONS//
//----------------------//
  unsigned short      atod_in;
  unsigned short int BATT_CHECK = 0;
  unsigned short int SCROLL = 0;
  unsigned short int SET_MODE = 0;
  unsigned short int IDLE_DETECT = 0;
  unsigned short int ALT = 0;
  unsigned short int End_Time = 0;
  unsigned short int End_Seg_Time = 0;
  unsigned short int Timer_On = 0;
  unsigned short int upload_run_flag = 0;
```

```
  unsigned short int Clin_Cnt_Flag = 0;
  INT16 len;

  /* System clock initialization */
  CLKSEL=0;
  CLKSEL_PLLSEL = 0;                /* Select clock source from XTAL */
  PLLCTL_PLLON = 0;                 /* Disable the PLL */
  SYNR = 0;                       /* Set the multiplier register */
  REFDV = 0;                       /* Set the divider register */
  PLLCTL = 192;
  PLLCTL_PLLON = 1;                 /* Enable the PLL */
  while(!CRGFLG_LOCK);               /* Wait */
  CRGFLG_PORF = 1;
  CLKSEL_PLLSEL = 1;                /* Select clock source from PLL */

  INTCR_IRQEN = 0;                  /* Disable the IRQ interrupt. IRQ interrupt is enabled after CPU reset by default. */

/*****************************/
/* Initialize ATD. */
/*****************************/

  DDRH    = 0x00;

  ATDCTL2 = 0xC0;
  ATDCTL3             = 0x48;
  ATDCTL4 = 0x83;
  ATDCTL5 = 0x30;

  DDRG    = 0x03;
  DDRT    = 0xC0;
  DDRJ    = 0x00;
  DDRB    = 0x00;
  DDRK    = 0xFF;


/*****************************/
/* Initialize LCD. */
/*   - 8 bit mode
/*****************************/
 LCD_Open(LCDINC+LCDNOSHIFT,
    LCDCURSOR+LCDNOBLINK,
    LCDNOSCROLL+LCDLEFT,
    LCD2LINE+LCD7DOT);


  Device_Mode = DIRECT_MAP;



/* Original Timer channel declaration for three distinct PWM duty cycles */
/*  -- Removed from final design                                          */
/*************************************************************************/
//TIOS = 0x30;  // Enable output compare on channel n (4)
//TIE = 0x20;   // Disable hardware interrupts from Timer
//OC7D = 0x00;  // Disable writing OC7 data reg to port //OC7D = 0x40;
//OC7M = 0x00;  // Do not set port to be a time output port
//TCTL1 = 0x40; // Toggle OCn output line on compare //0x00;

//TC5 = 500;
//CNT = 0;
//__asm CLI; //INTCR_IRQEN = 0; //EnableInterrupts;
/*************************************************************************/

// Start of Processing Loop
  for(;;) {
    SCROLL = 0;
    SET_MODE = 0;
    nextDevice_Mode = Device_Mode;
```

```
// while battery is still good
if (ATD_Peek(BATTERY) <= BATTERY_GOOD) {
  Device_Mode = POWER_DOWN;
}

// Direct Map Device Mode
if (Device_Mode == DIRECT_MAP) {
  Timer_On = 0;
  CNT = 0;
  LCD_WriteLine("Mode: Direct Map", 1);
  Display_Battery_Level(2);
  ALT = 0;
  End_Seg_Time = TCNT + 0xFB80;
  while (ATD_Peek(BATTERY) > BATTERY_GOOD) {
    //Actual Functionality
    Motor_Lookup();
    //Set_Motors_Encoded(Motor_Lookup()); to use PWM
    //  --  Not used in final design


     // No input currently detected - Turn on idle counter
     if (Timer_On == 0 && Motor_Out == 0x00) {
       Timer_On = 1;
       End_Time = TCNT + 0xFB80;
       CNT = 0;
     } else if (Motor_Out != 0x00) {
       Timer_On = 0;
     }

     // Count idle counter for specified time intervals
     if ((TCNT >= End_Time && (End_Time >= 0xFB80 || TCNT < 0xFB80))
           && Timer_On == 1) {
       CNT++;
       End_Time = TCNT + 0xFB80;
     }

     // Determine amount of time in Direct Map Mode - Subcounter
     if (TCNT >= End_Seg_Time && (End_Seg_Time >= 0xFB80 || TCNT < 0xFB80)) {
           DIRECT_SUBCOUNT++;
       End_Seg_Time = TCNT + 0xFB80;
     }
     // Determine amount of time in Direct Map Mode - Main counter
     if (DIRECT_SUBCOUNT > TIME_SEG) {
       DIRECT_SUBCOUNT = 0;
       DIRECT_COUNT++;
     }

     // Enter Power Conservation mode if system idle count goes above IDLE
     // threshold
     if (CNT > IDLE_TIME && Timer_On == 1) {
       //LCD_WriteLine("Entering IDLE...", 2);
       //swait();
       Device_Mode = POWER_DOWN;
       break;
     }

    // Determine if RPG scroll performed, if so display next mode on LCD
    if (PORTB_BIT1 != 1) {
      SCROLL = 1;
      Timer_On = 0;
    } else if (SCROLL == 1) {
      SCROLL = 0;
      nextDevice_Mode++;
      //TSCR1 &= ~0x90;
      //TSCR2 &= ~0x02;
      Display_nextMode(2);
      //TSCR1 = 0x90; // Enable Timer
      //TSCR2 = 0x02; // Timer reset on CH7 match, BUS CLOCK/4
      Timer_On = 0;
    }
```

```
    // Determine if RPG mode select performed, if so change modes
    if (PORTB_BIT0 == 0) {
      Device_Mode = (nextDevice_Mode % 3);
      Timer_On = 0;
      break;
    }
  }

  // Training Device Mode
} else if (Device_Mode == TRAINING) {
  LCD_WriteLine("Mode: Training  ", 1);
  Display_Battery_Level(2);
  Timer_On = 0;
  CNT = 0;

  while (   (Device_Mode == TRAINING)
        && (ATD_Peek(BATTERY) > BATTERY_GOOD)) {
    //Actual Functionality
    //  Reset counters, and check values back to 0 for new mode
    BATT_CHECK = 0;
    CNT = 0;
    Timer_On = 0;
    if (SET_MODE == 1) {
      Display_Battery_Level(2);
      SET_MODE = 0;
    }

    //Enter training algorithm
      // First step performed is raising the leg, check clinometer
    while ((ATD_Peek(CLINOMETER) < KNEE_BEND) && (Device_Mode == TRAINING)) {
      PORTK = 0xFF;
      PTT = 0xC0;
      Motor_Out = 0x3FF; // Vibrate all motors until leg raise detected.

      // No input currently detected - Turn on idle counter
      if (Timer_On == 0) {
        Timer_On = 1;
        End_Time = TCNT + 0xFB80;
        CNT = 0;
      }

      // Count idle counter for specified time intervals
      // Determine amount of time in Training Mode - Subcounter
      if ((TCNT >= End_Time && (End_Time >= 0xFB80 || TCNT < 0xFB80)) && Timer_On == 1) {
        CNT++;
        TRAIN_SUBCOUNT++;
        End_Time = TCNT + 0xFB80;
      }

     // Determine amount of time in Training Mode - Main counter
      if (TRAIN_SUBCOUNT > TIME_SEG) {
        TRAIN_SUBCOUNT = 0;
        TRAIN_COUNT++;
      }

      if (CNT > IDLE_TIME && Timer_On == 1) {
        //LCD_WriteLine("Entering IDLE...", 2);
        //swait();
        Device_Mode = POWER_DOWN;
        break;
      }



      // Enter Power Conservation mode if system idle count goes above IDLE
      // threshold
      if (ATD_Peek(BATTERY) <= BATTERY_GOOD) {
        BATT_CHECK = 1;
        //Power_Down_Leg();
```

```
    break;
  }

  // Determine if RPG scroll performed, if so display next mode on LCD
  if (PORTB_BIT1 != 1) {
    SCROLL = 1;
    Timer_On = 0;
  } else if (SCROLL == 1) {
    SCROLL = 0;
    nextDevice_Mode++;
    //TSCR1 &= ~0x90;
    //TSCR2 &= ~0x02;
    Display_nextMode(2);
    //TSCR1 = 0x90; // Enable Timer
    //TSCR2 = 0x02; // Timer reset on CH7 match, BUS CLOCK/4
    Timer_On = 0;
  }

  // Determine if RPG mode select performed, if so change modes
  if (PORTB_BIT0 == 0) {
    Device_Mode = (nextDevice_Mode % 3);
    SET_MODE = 1;
    Timer_On = 0;
    break;
  }
}

// Count step complete, increment training step counter
if (!SET_MODE && !BATT_CHECK && (Device_Mode == TRAINING)) {
  CLIN_COUNT++;
}


// Reset counters and checks for next step in training sequence
SCROLL = 0;
Timer_On = 0;
CNT = 0;

  // Second step performed is stepping on heel, check heel sensor
while (   (ATD_Peek(HEEL) < 0x40) && !BATT_CHECK && !SET_MODE
       && (Device_Mode == TRAINING)) {
  PORTK = 0x0C;
  PTT = 0x00;
  Motor_Out = 0x0C;  // Vibrate heel motors while sensor not depressed

  // Reset the step counter if clinometer not yet above threshold
  if (Clin_Cnt_Flag == 0) {
    Clin_Cnt_Flag = 1;
    CLIN_COUNT = 0;
  }

  if (CLIN_COUNT > (50 * TRAIN_COUNT)) {
    CLIN_COUNT = 0;
  }

  // No input currently detected - Turn on idle counter
  if (Timer_On == 0) {
    Timer_On = 1;
    End_Time = TCNT + 0xFB80;
    CNT = 0;
  }

  // Count idle counter for specified time intervals
  // Determine amount of time in Training Mode - Subcounter
  if ((TCNT >= End_Time && (End_Time >= 0xFB80 || TCNT < 0xFB80)) && Timer_On == 1) {
    CNT++;
    TRAIN_SUBCOUNT++;
    End_Time = TCNT + 0xFB80;
  }
```

```
 // Determine amount of time in Training Mode - Main counter
  if (TRAIN_SUBCOUNT > TIME_SEG) {
    TRAIN_SUBCOUNT = 0;
    TRAIN_COUNT++;
  }

  // Enter Power Conservation mode if system idle count goes above IDLE
  // threshold
  if (CNT > IDLE_TIME && Timer_On == 1) {
    //LCD_WriteLine("Entering IDLE...", 2);
    //swait();
    Device_Mode = POWER_DOWN;
    break;
  }

  // Enter Power Conservation mode if battery low
  if (ATD_Peek(BATTERY) <= BATTERY_GOOD) {
    BATT_CHECK = 1;
    //Power_Down_Leg();
    break;
  }

  // Determine if RPG scroll performed, if so display next mode on LCD
  if (PORTB_BIT1 != 1) {
    SCROLL = 1;
    Timer_On = 0;
  } else if (SCROLL == 1) {
    SCROLL = 0;
    nextDevice_Mode++;
    //TSCR1 &= ~0x90;
    //TSCR2 &= ~0x02;
    Display_nextMode(2);
    //TSCR1 = 0x90; // Enable Timer
    //TSCR2 = 0x02; // Timer reset on CH7 match, BUS CLOCK/4
    Timer_On = 0;
  }

  // Determine if RPG mode select performed, if so change modes
  if (PORTB_BIT0 == 0) {
    Device_Mode = (nextDevice_Mode % 3);
    SET_MODE = 1;
    Timer_On = 0;
    break;
  }
 }

 // Reset counters and checks for next stage of training mode
 SCROLL = 0;

 Timer_On = 0;
 CNT = 0;

  // Third step performed is stepping on ball of foot,
  // check ball of foot sensors
 while (   ((ATD_Peek(STRONG_SIDE) < 0x40) && (ATD_Peek(WEAK_SIDE) < 0x40))
       && !BATT_CHECK && !SET_MODE && (Device_Mode == TRAINING)) {
  PORTK = 0x73;
  PTT = 0x40;
  Motor_Out = 0x273;  // Vibrate ball of foot motors until sensor depressed

  // No input currently detected - Turn on idle counter
  if (Timer_On == 0) {
    Timer_On = 1;
    End_Time = TCNT + 0xFB80;
    CNT = 0;
  }

  // Count idle counter for specified time intervals
  // Determine amount of time in Training Mode - Subcounter
  if ((TCNT >= End_Time && (End_Time >= 0xFB80 || TCNT < 0xFB80)) && Timer_On == 1) {
```

```
    CNT++;
    TRAIN_SUBCOUNT++;
    End_Time = TCNT + 0xFB80;
   }

  // Determine amount of time in Training Mode - Main counter
   if (TRAIN_SUBCOUNT > TIME_SEG) {
    TRAIN_SUBCOUNT = 0;
    TRAIN_COUNT++;
   }

   // Enter Power Conservation mode if system idle count goes above IDLE
   // threshold
   if (CNT > IDLE_TIME && Timer_On == 1) {
    //LCD_WriteLine("Entering IDLE...", 2);
    //swait();
    Device_Mode = POWER_DOWN;
    break;
   }

   // Enter Power Conservation mode if battery low
   if (ATD_Peek(BATTERY) <= BATTERY_GOOD) {
    BATT_CHECK = 1;
    //Power_Down_Leg();
    break;
   }

   // Determine if RPG scroll performed, if so display next mode on LCD
   if (PORTB_BIT1 != 1) {
    SCROLL = 1;
    Timer_On = 0;
   } else if (SCROLL == 1) {
    SCROLL = 0;
    nextDevice_Mode++;
    //TSCR1 &= ~0x90;
    //TSCR2 &= ~0x02;
    Display_nextMode(2);
    //TSCR1 = 0x90; // Enable Timer
    //TSCR2 = 0x02; // Timer reset on CH7 match, BUS CLOCK/4
    Timer_On = 0;
   }

   // Determine if RPG mode select performed, if so change modes
   if (PORTB_BIT0 == 0) {
    Device_Mode = (nextDevice_Mode % 3);
    SET_MODE = 1;
    Timer_On = 0;
    break;
   }
  }

  // Reset counter and checks for next step in training mode
  SCROLL = 0;
  Timer_On = 0;
  CNT = 0;

  // Final step performed is stepping on toe, check toe sensor
  while (   (ATD_Peek(TOE) < 0x40) && !BATT_CHECK && !SET_MODE
        && (Device_Mode == TRAINING)) {
   PORTK = 0x80;
   PTT = 0x80;
   Motor_Out = 0x180;

   // No input currently detected - Turn on idle counter
   if (Timer_On == 0) {
    Timer_On = 1;
    End_Time = TCNT + 0xFB80;
    CNT = 0;
   }
```

```
      // Count idle counter for specified time intervals
      // Determine amount of time in Training Mode - Subcounter
      if ((TCNT >= End_Time && (End_Time >= 0xFB80 || TCNT < 0xFB80)) && Timer_On == 1) {
        CNT++;
        TRAIN_SUBCOUNT++;
        End_Time = TCNT + 0xFB80;
      }

     // Determine amount of time in Training Mode - Main counter
      if (TRAIN_SUBCOUNT > TIME_SEG) {
        TRAIN_SUBCOUNT = 0;
        TRAIN_COUNT++;
      }

      // Enter Power Conservation mode if system idle count goes above IDLE
      // threshold
      if (CNT > IDLE_TIME && Timer_On == 1) {
        //LCD_WriteLine("Entering IDLE...", 2);
        //swait();
        Device_Mode = POWER_DOWN;
        break;
      }

      // Enter Power Conservation mode if battery low
      if (ATD_Peek(BATTERY) <= BATTERY_GOOD) {
        BATT_CHECK = 1;
        //Power_Down_Leg();
        break;
      }

      // Determine if RPG scroll performed, if so display next mode on LCD
      if (PORTB_BIT1 != 1) {
        SCROLL = 1;
        Timer_On = 0;
      } else if (SCROLL == 1) {
        SCROLL = 0;
        nextDevice_Mode++;
        //TSCR1 &= ~0x90;
        //TSCR2 &= ~0x02;
        Display_nextMode(2);
        //TSCR1 = 0x90; // Enable Timer
        //TSCR2 = 0x02; // Timer reset on CH7 match, BUS CLOCK/4
        Timer_On = 0;
      }

      // Determine if RPG mode select performed, if so change modes
      if (PORTB_BIT0 == 0) {
        Device_Mode = (nextDevice_Mode % 3);
        SET_MODE = 1;
        Timer_On = 0;
        break;
      }
     }
     SCROLL = 0;
     //TSCR1 &= ~0x90;
     //TSCR2 &= ~0x02;
    }

  // Upload data mode
  } else if (Device_Mode == UPLOAD) {
    //Power_Down_Leg();
    // Turn Motors and counters off
    PORTK = 0x00;
    PTT = 0x00;
    Motor_Out = 0x00;
    LCD_WriteLine("Mode: Upload    ", 1);
    Display_Battery_Level(2);
    Timer_On = 0;
    CNT = 0;
```

```
    // Enter Power Conservation mode if battery low
    while (ATD_Peek(BATTERY) > BATTERY_GOOD) {
      //Actual Functionality

      // INITIALIZE ETHERNET MODULE
      if(upload_run_flag == 0){
        E_init();
        upload_run_flag = 1;
      }

      // RUN ETHERNET MODULE
      E_run();

      // Determine if RPG scroll performed, if so display next mode on LCD
      if (PORTB_BIT1 != 1) {
        SCROLL = 1;
      } else if (SCROLL == 1) {
        SCROLL = 0;
        nextDevice_Mode++;
        Display_nextMode(2);
      }

      // Determine if RPG mode select performed, if so change modes
      if (PORTB_BIT0 == 0) {
        Device_Mode = (nextDevice_Mode % 3);
        upload_run_flag = 0;
        TSCR1 = 0x80;   // Enable TCNT, 24MHz boot mode, 4MHz in run mode
        //TSCR2 = 0x05;   // divide by 16 TCNT prescale, TCNT at 667nsec
        // TSCR1 = 0x80;   // Enable TCNT, 24MHz boot mode, 4MHz in run mode
        TSCR2 = 0x04;   // divide by 16 TCNT prescale, TCNT at 667nsec
        PACTL = 0;      // timer prescale used for TCNT
        break;
      }
    }

   // Power Down Mode
   } else { //(Device_Mode == POWER_DOWN) {
     LCD_WriteLine("Mode: Power Down", 1);
     //if (ATD_Peek(BATTERY) <= BATTERY_GOOD) {
       Power_Down_Leg();
       //LCD_WriteLine("Replace Battery!", 2);
       //while (ATD_Peek(BATTERY) <= BATTERY_GOOD); // in case of temporary fluctuation
       for(;;){
       }
   }
 }

  // Battery is weak


  for(;;){
  }

////////////////////////////////////////////////////////////////
```

Ethernet Code:

```
/************************/
/* Init Ethernet Module */
/************************/
 void E_init();

/************************/
/* Run Ethernet Module */
/************************/
 void E_run();

/*******************************/
/* Initialize Ethernet Module */
```

```
/*******************************/
void E_init() {

   init();
            /* IP address */
              localmachine.localip = *((UINT32 *)ip_address);
            /* Default gateway */
            localmachine.defgw   = *((UINT32 *)ip_gateway);
            /* Subnet mask */
            localmachine.netmask = *((UINT32 *)ip_netmask);

            /* Ethernet (MAC) address */
            localmachine.localHW[0] = hard_addr[0];
            localmachine.localHW[1] = hard_addr[1];
            localmachine.localHW[2] = hard_addr[2];
            localmachine.localHW[3] = hard_addr[3];
            localmachine.localHW[4] = hard_addr[4];
            localmachine.localHW[5] = hard_addr[5];

            /* Init system services                         */
            timer_pool_init();

   /* Initialize all buffer descriptors */
            mBufInit ();

            /* Initialize all network layers   */
  EtherInit();

  /* Initialize TCP and HTTP protocols */
  (void)tcp_init();
            (void)https_init ();

            return;
}


/************************/
/* Run Ethernet Module */
/************************/
void E_run() {
   INT16 len;

                        if( NETWORK_CHECK_IF_RECEIVED() == TRUE ) {
                                switch( received_frame.protocol)
                                 {
                                        case PROTOCOL_ARP:
                                                process_arp (&received_frame);
                                        break;
                                        case PROTOCOL_IP:
                                                len = process_ip_in(&received_frame);
                                                if(len < 0)
                                                        break;
                                                switch (received_ip_packet.protocol)
                                                  {
                                                        case IP_ICMP:
                                                        process_icmp_in (&received_ip_packet, len);
                                                                break;
                                                        case IP_UDP:
                                                       process_udp_in (&received_ip_packet,len);
                                                                break;
                                                        case IP_TCP:
                                                        process_tcp_in (&received_ip_packet, len);
                                                                break;
                                                        default:
                                                                break;
                                                }
                                        break;
                                          default:
                                          break;
                                }
```

```
                                /* discard received frame */
                                NETWORK_RECEIVE_END();
                        }

                        /* Application main loops */
                        /* TCP/IP stack Periodic tasks here... */
                tcp_poll();  //Poll to see if connection established
    https_run ();  //Serve webpage data
}
////////////////////////////////////////////////////////
```

LCD Code:

```
/*************************/
/*LCD FUNCTION DEFINITIONS*/
/*************************/

void lcdDelay(unsigned long constant) {
  volatile unsigned long counter;

  for (counter = constant; counter > 0; counter--);
}

//---------------------wait---------------------
// time delay
// Input: time in 0.667usec
// Output: none
void static wait(unsigned short delay){ short TimeLeft,EndT;
  EndT = TCNT+delay;        /* Time (0.667us cycles) to wait */
  do{
    TimeLeft = (short)TCNT-EndT;
  }
  while((TimeLeft<0)||(TimeLeft>100));   // wait

}

//---------------------LCD_Clear---------------------
// clear the LCD display, send cursor to home
// Input: none
// Output: true if successful
short LCD_Clear(void){
  if(OpenFlag==0){
    return 0;  // not open
  }

  //CLEAR DISPLAY
  PTG_PTG6 = 0; //DB7
  PTG_PTG5 = 0; //DB6
  PTG_PTG3 = 0; //DB5
  PTG_PTG2 = 0; //DB4
  PTG_PTG1 = 0; //DB3
  PTG_PTG0 = 0; //DB2
  PORTB_BIT7 = 0; //DB1
  PORTB_BIT6 = 1; // DB0

  PORTB_BIT5 = 1; //E
  PORTB_BIT5 = 0;
  wait(150);

  wait(2600);

  //CURSOR TO HOME
  PTG_PTG6 = 0; //DB7
  PTG_PTG5 = 0; //DB6
  PTG_PTG3 = 0; //DB5
  PTG_PTG2 = 0; //DB4
  PTG_PTG1 = 0; //DB3
  PTG_PTG0 = 0; //DB2
  PORTB_BIT7 = 1; //DB1
  PORTB_BIT6 = 0; // DB0
```

```
  PORTB_BIT5 = 1; //E
  PORTB_BIT5 = 0;
  wait(150);
  wait(2600);

  return 1;                     // success
}


//---------------------LCD_Open---------------------
// initialize the LCD display, called once at beginning
// Input: display determines increment and shift option
//        cursor determines cursor options
//        move determines cursor movement
//        size sets display size
// Output: true if successful
short LCD_Open(char display, char cursor, char move, char size){
  if(OpenFlag){
    return 0;  // already open
  }
 DDRB |= 0xF8;  // LCD Control Bits
 DDRG |= 0x6F;        // LCD Data Bits
 TSCR1 = 0x80;   // Enable TCNT, 24MHz boot mode, 4MHz in run mode
 TSCR2 = 0x04;   // divide by 16 TCNT prescale, TCNT at 667nsec
 PACTL = 0;      // timer prescale used for TCNT

 PORTB_BIT4 = 0;
 PORTB_BIT3 = 0;

 PTG_PTG6 = 0; //DB7
 PTG_PTG5 = 0; //DB6
 PTG_PTG3 = 1; //DB5
 PTG_PTG2 = 1; //DB4
 PTG_PTG1 = 0; //DB3
 PTG_PTG0 = 0; //DB2
 PORTB_BIT7 = 0; //DB1 - Increment Display
 PORTB_BIT6 = 0; // DB0 - No shift

 PORTB_BIT5 = 1; //E
 PORTB_BIT5 = 0;
 wait(150);

  //DISPLAY
  PTG_PTG6 = 0; //DB7
  PTG_PTG5 = 0; //DB6
  PTG_PTG3 = 0; //DB5
  PTG_PTG2 = 0; //DB4
  PTG_PTG1 = 0; //DB3
  PTG_PTG0 = 1; //DB2
  PORTB_BIT7 = 1; //DB1 - Increment Display
  PORTB_BIT6 = 0; // DB0 - No shift

  PORTB_BIT5 = 1; //E
  PORTB_BIT5 = 0;
  wait(150);

  //CURSOR
  PTG_PTG6 = 0; //DB7
  PTG_PTG5 = 0; //DB6
  PTG_PTG3 = 0; //DB5
  PTG_PTG2 = 0; //DB4
  PTG_PTG1 = 1; //DB3
  PTG_PTG0 = 1; //DB2
  PORTB_BIT7 = 1; //DB1 - No cursor
  PORTB_BIT6 = 0; // DB0 - No blink

  PORTB_BIT5 = 1; //E
  PORTB_BIT5 = 0;
  wait(150);
```

```
  //MOVE
  PTG_PTG6 = 0; //DB7
  PTG_PTG5 = 0; //DB6
  PTG_PTG3 = 0; //DB5
  PTG_PTG2 = 1; //DB4
  PTG_PTG1 = 0; //DB3
  PTG_PTG0 = 0; //DB2
  PORTB_BIT7 = 0; //DB1
  PORTB_BIT6 = 0; // DB0

  PORTB_BIT5 = 1; //E
  PORTB_BIT5 = 0;
  wait(150);

  //SIZE
  PTG_PTG6 = 0; //DB7
  PTG_PTG5 = 0; //DB6
  PTG_PTG3 = 1; //DB5
  PTG_PTG2 = 1; //DB4  8-bit mode
  PTG_PTG1 = 1; //DB3  2 line mode
  PTG_PTG0 = 0; //DB2           Dot pitch
  PORTB_BIT7 = 0; //DB1
  PORTB_BIT6 = 0; // DB0
  PORTB_BIT5 = 1; //E
  PORTB_BIT5 = 0;
  wait(150);

  OpenFlag = 1;         // device open
  return LCD_Clear();   // clear display
}

//---------------------LCD_OutChar---------------------
// sends one ASCII to the LCD display
// Input: letter is ASCII code
// Output: true if successful

short LCD_WriteLine(char *letter, unsigned int line) {
  if (line == 1) {
    //PORTB &= ~0x38;
    PORTB_BIT5 = 0;
    PORTB_BIT4 = 0;
    PORTB_BIT3 = 0;

    //WRITE TO LINE 1
    PTG_PTG6 = 1; //DB7
    PTG_PTG5 = 0; //DB6
    PTG_PTG3 = 0; //DB5
    PTG_PTG2 = 0; //DB4
    PTG_PTG1 = 0; //DB3
    PTG_PTG0 = 0; //DB2
    PORTB_BIT7 = 0; //DB1
    PORTB_BIT6 = 0; // DB0

    PORTB_BIT5 = 1; //E
    PORTB_BIT5 = 0;
    wait(150);

    return LCD_OutString(letter);
  } else{
    //PORTB &= ~0x38;
    PORTB_BIT5 = 0;
    PORTB_BIT4 = 0;
    PORTB_BIT3 = 0;

    //WRITE TO LINE 2
    PTG_PTG6 = 1; //DB7
    PTG_PTG5 = 1; //DB6
    PTG_PTG3 = 0; //DB5
    PTG_PTG2 = 0; //DB4
```

```
    PTG_PTG1 = 0; //DB3
    PTG_PTG0 = 0; //DB2
    PORTB_BIT7 = 0; //DB1
    PORTB_BIT6 = 0; // DB0

    PORTB_BIT5 = 1; //E
    PORTB_BIT5 = 0;
    wait(150);

    return LCD_OutString(letter);
  }
}

short LCD_OutChar(unsigned char letter){
  //unsigned char temp = letter;
  if(OpenFlag==0){
    return 0;  // not open
  }

  PORTB_BIT3 = 1;

  if ( (letter&0x80) == 0x80) {
    PTG_PTG6 = 1;
  }else{

    PTG_PTG6 = 0;
  }

  if ( (letter&0x40) == 0x40) {
    PTG_PTG5 = 1;
  }else{

    PTG_PTG5 = 0;
  }

  if ( (letter&0x20) == 0x20) {
    PTG_PTG3 = 1;
  }else{

    PTG_PTG3 = 0;
  }

  if ( (letter&0x10) == 0x10) {
    PTG_PTG2 = 1;
  }else{

    PTG_PTG2 = 0;
  }

  if ( (letter&0x08) == 0x08) {
    PTG_PTG1 = 1;
  }else{

    PTG_PTG1 = 0;
  }

  if ( (letter&0x04) == 0x04) {
    PTG_PTG0 = 1;
  }else{

    PTG_PTG0 = 0;
  }

  if ( (letter&0x02) == 0x02) {
    PORTB_BIT7 = 1;
  }else{

    PORTB_BIT7 = 0;
  }
```

```
  if ( (letter&0x01) == 0x01) {
    PORTB_BIT6 = 1;
  }else{

    PORTB_BIT6 = 0;
  }

  PORTB_BIT5 = 1;
  PORTB_BIT5 = 0;


  PORTB_BIT3 = 0;

  wait(150);          // 90 us wait
  return 1;           // success
}




//---------------------LCD_OutString--------------
// Display String
// Input: pointer to NULL-terminationed ASCII string
// Output: true if successful
short LCD_OutString(char *pt){
  if(OpenFlag==0){
    return 0;  // not open
  }
  while(*pt){
    if(LCD_OutChar((unsigned char)*pt)==0){
      return 0;
    }
    pt++;
  }
  return 1;   // success
}

//---------------------wait----------------------
// time delay
// Input: time in 0.667usec
// Output: none
void static wait(unsigned short delay){ short TimeLeft,EndT;
  EndT = TCNT+delay;        /* Time (0.667us cycles) to wait */
  do{
    TimeLeft = (short)TCNT-EndT;
  }
  while((TimeLeft<0)||(TimeLeft>100));   // wait

}
```

HTTP Web Server Code:

```
signed char ctd[10]={ '0','1','2','3','4','5','6','7','8','9'};

signed char* DEC_TO_ASCII(UINT16 c);

signed char* DEC_TO_ASCII(UINT16 c){

  signed char s[5];
  UINT16 divider;
  UINT8 leaddigit;
  UINT8 foundmsd;
  UINT8     j;

  divider = 1000;
  j = 0;
  foundmsd = FALSE;
  //div 1000
  leaddigit = (UINT8)(c / divider);
  if  (leaddigit == 0) {
```

```
   s[j] = ctd[0];
   divider = divider/10;
   j++;
  }
  else {
   s[j] = ctd[leaddigit];
   c = c - leaddigit * divider;
   divider = divider/10;
   j=j+1;
   foundmsd = TRUE;
  }
  //div 100
  leaddigit = (UINT8)(c / divider);
  if  ((leaddigit == 0) && (!foundmsd)) {
   s[j] = ctd[0];
   divider = divider/10;
   j++;
  }
  else {
   s[j] = ctd[leaddigit];
   c = c - leaddigit * divider;
   divider = divider/10;
   j=j+1;
   foundmsd = TRUE;
  }
  //div 10
  leaddigit = (UINT8)(c / divider);
  if  ((leaddigit == 0) && (!foundmsd)) {
   s[j] = ctd[0];
   divider = divider/10;
   j++;
  }
  else {
   s[j] = ctd[leaddigit];
   c = c - leaddigit * divider;
   divider = divider/10;
   j=j+1;
   foundmsd = TRUE;
  }
  //div 1
  leaddigit = (UINT8)(c / divider);
  s[j] = ctd[leaddigit];
  j=j+1;
  s[j]=0;
  return s;

}
```

Modified LoadBuffer Function:

```
/** \brief Fill network transmit buffer with HTTP headers&data
 *          \author
 *                  \li Jari Lahti (jari.lahti@violasystems.com)
 *          \date 09.10.2002
 *          \param ses HTTP session identifier
 *          \param buf Pointer to buffer where data is to be stored
 *          \param buflen Length of the buffer in bytes
 *          \return
 *                  \li >=0 - Number of bytes written to buffer
 *          \warning
 *                  \li This function <b>MUST</b> be implemented by user application
 *                  to work with local configuration
 *
 *          This handlers' job is to fill the buffer with the data that web server
 *          should return back through the TCP connection. This is accomplished
 *          based session identifer and values of variables in appropriate
 *          https entry.
 */
```

```
INT16 https_loadbuffer (UINT8 ses, UINT8* buf, UINT16 buflen)
{
        UINT16 i, j;
        signed char *steped;
        extern UINT16 DIRECT_COUNT;
        extern UINT16 TRAIN_COUNT;
        extern UINT16 TOTAL_COUNT;
        extern UINT16 CLIN_COUNT;

  char *varA = "DIR TIME = ";
  char *varB = "TRAIN TIME = ";
  char *varC = "TOTAL TIME = ";
  char *varD = "STEPS TAKEN = ";
  char *varBR = "<BR>";

  j = 0;


        if( https[ses].fstart == (void *)(~0) )
        {
                kick_WD();

    https[ses].flen = 83;

    //VAR A OUTPUT
    for(j = 0; j < 11; j++){
      *buf++ = varA[j];
      i++;
    }

    steped = DEC_TO_ASCII(DIRECT_COUNT);

    for(j = 0; j < 4; j++) {
      *buf++ = steped[j];
      i++;
    }

    for(j = 0; j < 4; j++){
      *buf++ = varBR[j];
      i++;
    }
    //VAR A OUTPUT END

    //VAR B OUTPUT
    for(j = 0; j < 13; j++){
      *buf++ = varB[j];
      i++;
    }

    steped = DEC_TO_ASCII(TRAIN_COUNT);

    for(j = 0; j < 4; j++) {
      *buf++ = steped[j];
      i++;
    }

    for(j = 0; j < 4; j++){
      *buf++ = varBR[j];
      i++;
    }
    //VAR B OUTPUT END

    //VAR C OUTPUT
    for(j = 0; j < 13; j++){
      *buf++ = varC[j];
      i++;
    }

    TOTAL_COUNT = DIRECT_COUNT + TRAIN_COUNT;
```

```
    steped = DEC_TO_ASCII(TOTAL_COUNT);

    for(j = 0; j < 4; j++) {
      *buf++ = steped[j];
      i++;
    }

    for(j = 0; j < 4; j++){
      *buf++ = varBR[j];
      i++;
    }
    //VAR C OUTPUT END

    //VAR D OUTPUT
    for(j = 0; j < 14; j++){
      *buf++ = varD[j];
      i++;
    }

    steped = DEC_TO_ASCII(CLIN_COUNT);

    for(j = 0; j < 4; j++) {
      *buf++ = steped[j];
      i++;
    }

    for(j = 0; j < 4; j++){
      *buf++ = varBR[j];
      i++;
    }
    //VAR D OUTPUT END

                    return(i);

            }
}
```

Appendix G: User Manual

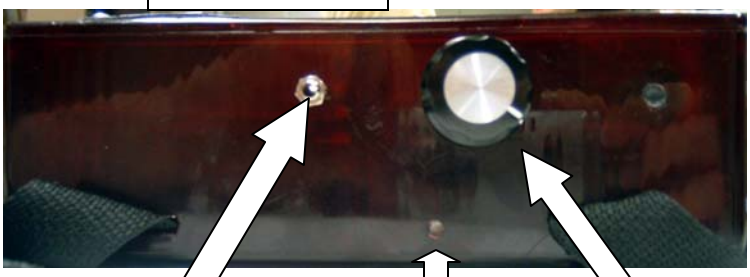
G.1 Introduction

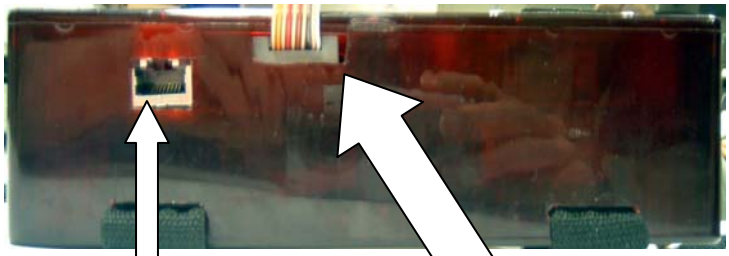
Thank you for choosing the General Informative Medical Prosthetic (G.I.M.P.). This system Is designed as an addition to a typical prosthetic leg and will assist you in the use of you medical prosthetic by providing a sensory feedback of the pressures being placed on the bottom of the prosthetic foot. For users who are still learning to walk with their prosthetics, the system also provides a training mode to help them learn to walk properly

The G.I.M.P. system will help users maintain balance by monitoring four thin pressure sensors placed in the sole of a typical shoe and a clinometer attached to the calf which measures the angle of the lower leg. Microcontroller circuitry worn on the calf then conveys the pressures detected to the user through a cloth strap containing ten vibration motors worn around the thigh. Depending on where pressure on the foot is detected the motors will vibrate at the front, back, left, or right side of the thigh. The control circuitry may be contained in a box strapped to the prosthetic calf, or ideally, it can be placed in the core of the prosthetic to reduce excess bulk added to the prosthetic.

The system will also help those new to using a prosthetic device learn to walk correctly with their prosthetic. The system has a training mode designed to teach the user how to walk by vibrating the motor strap in a particular order to indicate to the user which way they need to move or apply pressure to the prosthetic. In addition the system is capable of recording data about the device usage for review by a doctor or therapist.

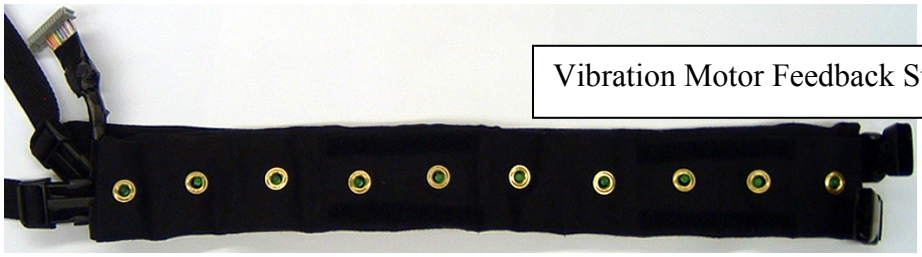
Front View





Clinometer

Foot Sensors



G.2 Setup Instructions

Note: The setup instructions are based on the control system residing in a box outside of the prosthetic. If the system has been integrated into your prosthetic, setup will not require attaching the control box and the locations of the control and batter may be different.

G.3 Installing the battery

Loosen the screw in the control knob and remove it. Then remove the retaining nut from the control knob shaft. Remove the six screws securing the top of the case and lay the top to the side being careful not to pull out the cable attached to the LCD screen. Remove the retaining nut from the power switch and remove it from it's hole in the case. Gently pull up on the circuit board on the side opposite the control knobs until it is free from the case and lay it to the side as well. Place a 7.2 volt RC battery in the battery straps located in the bottom of the case and connect it to the battery cable of the circuit board. Replace the circuit board in the case by placing the control knob shaft through the appropriate hole in the case and then gently pressing the opposite side of the board into place. Replace the power switch and refasten the top of the case and reattach the retaining nut and control knot to the control knob shaft.

G.4 Wearing the device

Secure the control box to the calf of the leg using the straps on the back of the box. The motor cable should be at the top of the calf. Then wrap the motor feedback strap around your thigh fastening the attached clip so that it is tight, but not so tight that it becomes uncomfortable. Connect the plug of the motor strap to the motor strap cable of the control box. Then fasten the

Note: The motor feedback strap may be worn over or underneath clothing will reduce the ability to fell vibration feedback

clinometer strap to the prosthetic just below the knee making sure the clinometer is on the side of the leg. Connect the clinometer to the control box using the appropriate plug. Finally, put on the shoe containing the sensors and connect it to the sensor cable of the control box.

G.5 Use Instructions

The General Informative Medical Prosthetic has 3 different modes: direct map, training, and upload. The current mode and battery level are displayed on the LCD located on the front of the control box. The current mode is displayed on the top line and the battery lever is indicated

by the number of # symbols on the bottom line. More # symbols indicate a stronger charge and no symbols indicate a dead battery. On startup the device is in direct map mode. Turning the control knob scrolls the display through the modes and pressing the knob selects the mode shown on the bottom line as the current mode.

In direct map mode, the device vibrates a certain pattern of motors in the feedback strap in response to pressures detected by the sensors in the sole of the shoe. For example, pressure on the heel of the foot will activate motors at the back of the strap while pressures on the toe will activate motors at the front of the strap.

In training mode, the device vibrates the motors in a sequence to indicate to the user the next action needed in the process of taking a step. The actions indicated by the motor combinations are indicated in the following table.

Training Mode Motor Patterns	
all motors on	lift leg
back motors on	apply pressure to heel of foot
side motors on	apply pressure to ball of foot
front motors on	apply pressure to toes

Once the correct action is detected by the sensors, the motors for the completed step are turned off and the motors for the nest step of the sequence are activated.

In upload mode, the device can be connected to a computer using a standard network crossover cable and statistics about the device usage can be viewed by a standard web browser. Entering the IP address 192.190.2.5 in the address bar of the browser will trigger the device to display the usage data currently stored in the device to the browser window.

G.6 Troubleshooting

Problem: Device will not power on.
Solutions: Check the battery level. Make sure the battery connection is secure and retry.

Problem: Device powers on but the screen is blank.
Solution: Adjust the LCD contrast using a small screwdriver. If the screen still does not

function properly remover the top of the control box and make sure the cable connection the LCD to the circuit board is securely connected and reset the device.

Problem: Motors do not vibrate.

Solution: Make sure the device is in the proper mode. If the device is in the correct mode try resetting the device. If the motors sill do not vibrate make sure all cable connections are secure and check the battery level.

If troubleshooting does not solve your problem contact the manufacturer for additional troubleshooting options, service or replacement.

Appendix H: FMECA Worksheet

The design schematic has been divided up into four functional blocks for the Failure Mode, Effects and Criticality analysis. These four blocks are the Microcontroller (A), Power Supply (B), Pressure Sensor Amplifier/Filters (C) and the Class D Motor Amplifiers (D). Throughout this worksheet, a failure marked as "Low Criticality" is defined as one which poses no safety risk, but will result in customer dissatisfaction. A failure rate of 10^{-6} will be considered acceptable for failures of "Low Criticality." A failure marked "Semi-Critical" could potentially cause a safety hazard for the user, and has an acceptable failure rate of 10^{-8}. The reason 10^{-8} was determined to be acceptable is described in the reliability analysis conclusions from the previous page. A failure marked "High Criticality" has been determined to yield a greater injury risk than the "Semi-Critical" failure just mentioned, and will use the standard 10^{-9} as the acceptable failure rate for failures possibly resulting in person injury to the user.

Failure No.	Failure Mode	Possible Causes	Failure Effects	Method of Detection	Criticality	Remarks
A1	Incorrect (constant) motor outputs	Microcontroller malfunction	Incorrect motors are constantly vibrated, possible confusion if walking dependence exists	Observation	High Criticality	
A2	Incorrect (changing) motor outputs	Software	Incorrect motors are vibrated, possible user confusion over walking instructions	Observation	High Criticality	

A3	Incorrect LCD output	Software, microcontroller malfunction	Incorrect or unreadable display, possible user confusion over current system mode when looking at LCD or inability to change system mode	Observation	Low Criticality	
B1	V_5, V_{-5} or $V_{3.3}$ out of tolerance	Malfunctioning regulator, malfunctioning transformer, shorted bypass capacitor, low battery	Possible damage to microcontroller or other components	Observation, ATD on micro (for detecting low battery)	High criticality	
B2	Unacceptable noise on V_5, V_{-5} or $V_{3.3}$	Shorted bypass capacitor	Possible damage to microcontroller or incorrect operation	Observation	High Criticality	
C1	Sensors always output low to the micro	Malfunctioning op amps, sensors out of condition	Motors never vibrate in “walking” mode, “learning” mode is non-functional, possible confusion if walking dependence exists	Observation	High Criticality	

C2	Sensors always output high to the micro	Malfunctioning op amps, sensors out of condition	Motors all always vibrate in “walking” mode, “learning” mode is non-functional, possible confusion if walking dependence exists	Observation	High Criticality	
C3	Sensors output some (incorrect) combination of highs and lows to the micro	Malfunctioning op amps, sensors out of condition	Motor reaction in “walking” mode is constant and incorrect, “learning” mode is non-functional, possible confusion if walking dependence exists	Observation	High Criticality	
D1	One motor is always vibrating	Malfunctioning transistor	Possible user confusion over walking instructions / sensations	Observation	Semi-Critical	
D2	Multiple motors are always vibrating	Multiple malfunctioning transistors	Possible user confusion over walking instructions / sensations	Observation	High Criticality	Multiple D1’s occur
D3	One motor is never vibrating	Malfunctioning transistor	Possible user confusion over walking instructions / sensations	Observation	Semi-Critical	
D4	Multiple motors are never vibrating	Multiple malfunctioning transistors	Possible user confusion over walking instructions / sensations	Observation	High Criticality	Multiple D3’s occur